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EVALUATION OF SHELTER VENTILATION BY MODEL TESTS - OPTION 2

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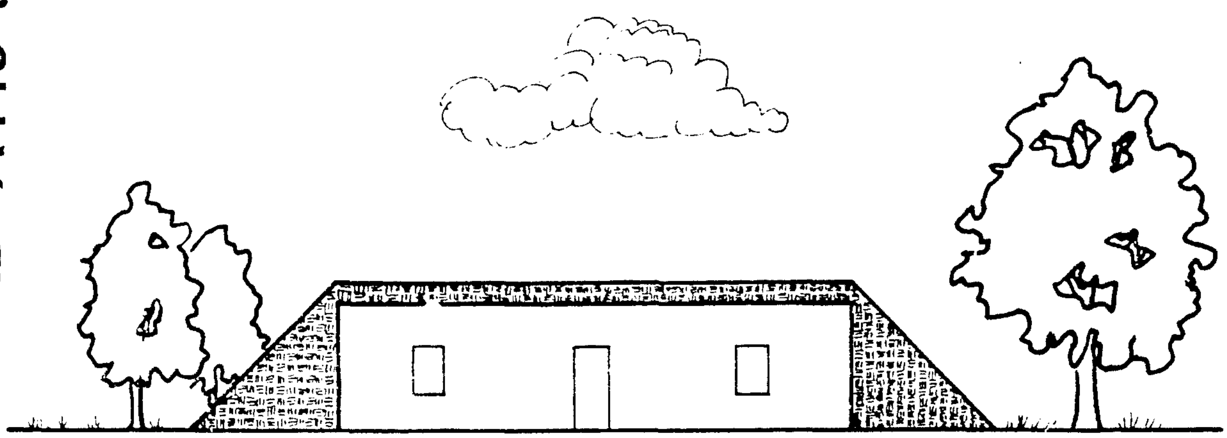
GARD FINAL REPORT A1-51



PREPARED FOR:
FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON, D.C. 20472

FEMA CONTRACT NO. EMW-C-0633
FEMA WORK UNIT 12171

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EVALUATION OF SHELTER VENTILATION BY MODEL TESTS - OPTION 2

GARD FINAL REPORT A1-51

September, 1984

FEMA Work Unit 1217I

by

C. K. Krishnakumar
C. K. Schafer
S. F. Fields
R. H. Henninger

for

Donald A. Bettge
FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, D.C. 20472

Under Contract No. EMW-C-0633

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DETACHABLE SUMMARY

EVALUATION OF SHELTER VENTILATION BY MODEL TESTS - OPTION 2

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June, 1984

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INTRODUCTION

This study represents the work performed during the third year of a multi-year Shelter Ventilation Analysis Program. The specific objective of the present study was to determine a correlation between the dependent variable - the shelter ventilation rate - and the independent variables influencing it. Independent variables analyzed in this study include, total area of wall openings, area ratio of windward to leeward wall openings, speed of approach wind and relative wind angle.

The approach taken to achieve the stated objective consisted of several series of wind tunnel tests using a scale model of the fallout shelter studied in the first year program. The total area of wall openings and their distribution over the walls were varied and the model ventilation rates were measured over a wide range of approach wind speeds and relative wind angles. Ventilation rates for the full-scale shelter were then projected from the model results using scaling laws.

METHOD AND PROCEDURE OF TESTING

Fallout shelters with five distinct opening configurations were modeled in this study. All shelters had the same length (48 feet), width (32 feet) and height (12 feet) as the one studied in the first year program. However, the total area of the openings varied from 2.5% to 3.44% of the exterior wall surface. Opening distribution patterns were also varied.

Since all five shelters had the same overall dimensions, the different opening configurations were obtained from the same basic model by using close-fitting aluminum wedges and plates to block off, open up or modify one or more of the openings. Figure 1 shows the basic model with the aluminum wedges partially drawn out. Figures 2-6 show the test models with the roofs removed.

After establishing the desired velocity profile for the approach air stream, the following four series of tests were performed to determine model ventilation rates at different values of the approach air stream velocity.

In the first series of tests, air volume flow rates through calibration tubes attached to the leeward openings of the models were correlated with measurements of axial velocities at a section 15 diameters downstream of the leading edge of these tubes. This was done by forcing metered volume flow rates of air through one of the wall openings of the shelter and simultaneously recording anemometer readings of air flow velocities in the tube. In the second series of tests, actual values of ventilation rates through the model with tubes attached to the leeward openings were determined for different velocities of the approach air stream. Test Series 3 and 4 were performed to determine the "tube correction factor" which is the factor by which the ventilation rates with the tubes (obtained from Test Series 2) should be multiplied to get actual values of model ventilation rates. Values, of this factor for different approach wind velocities were determined by taking ratios of average flow velocities across the main windward opening obtained without tubes at the leeward openings to those obtained when tubes were attached to the leeward openings. Average flow velocities through the main windward openings were obtained by determining the average velocities of tracer bubbles passing through them using motion photography.

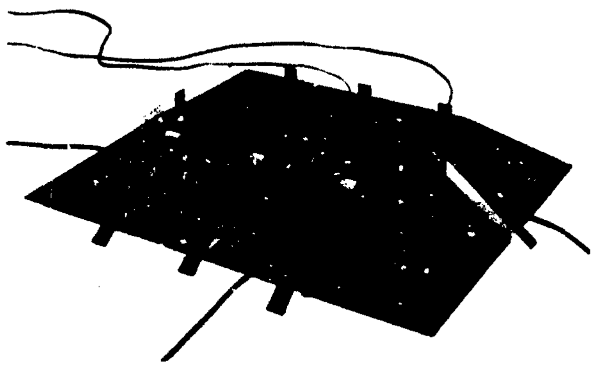

Figure 1 SHELTER MODEL WITH WEDGES PARTIALLY PULLED OUT

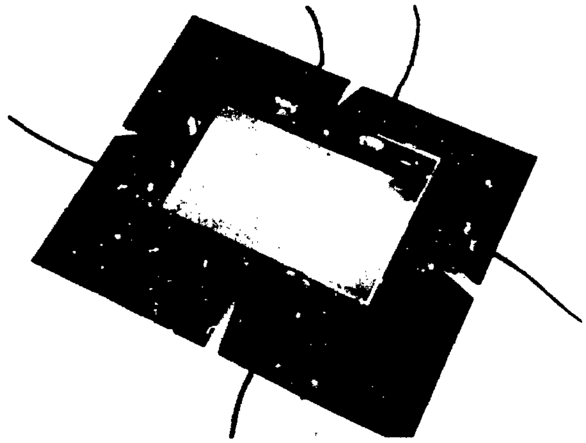

Figure 2 MODEL CONFIGURATION - A

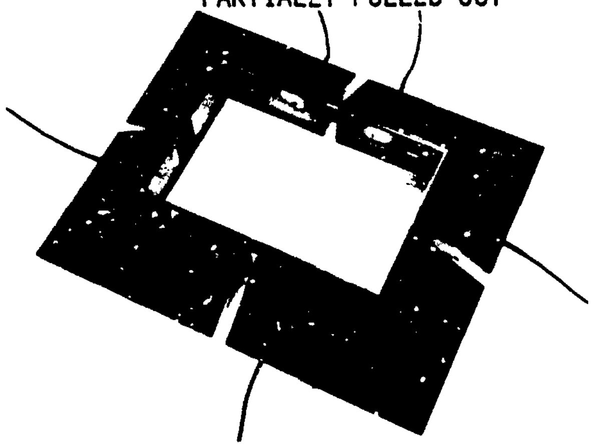

Figure 3 MODEL CONFIGURATION - B

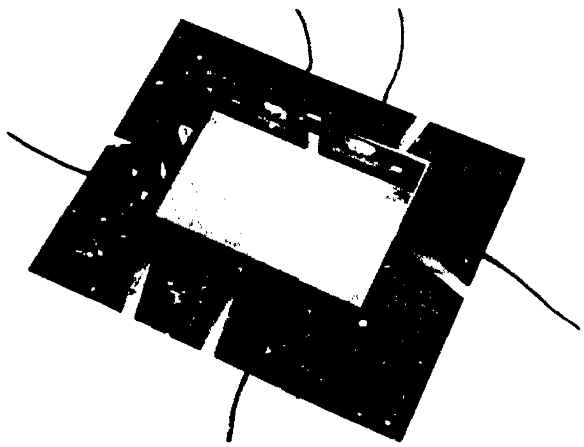

Figure 4 MODEL CONFIGURATION - C

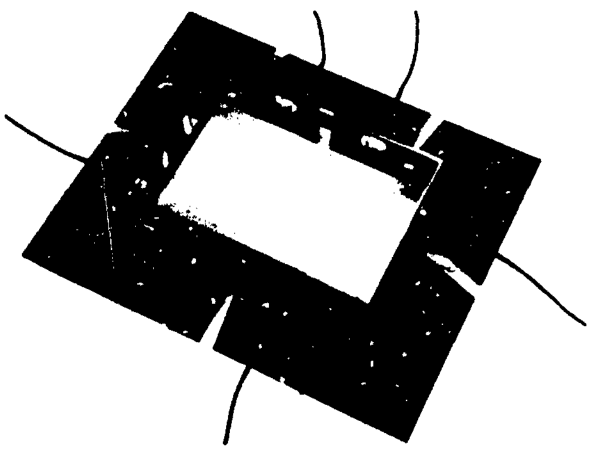

Figure 5 MODEL CONFIGURATION - D

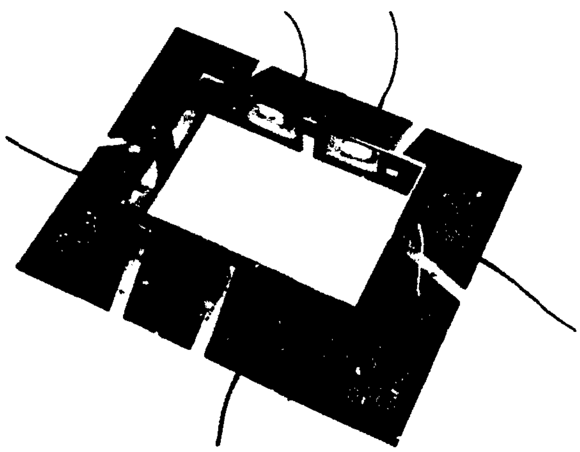

Figure 6 MODEL CONFIGURATION - E

RESULTS OF MODEL TESTS

Based on the model test data, the following linear relation was generated between the dependent variable of shelter ventilation rate and the independent variables of approach wind velocity, windward opening area and a factor F whose value depends on the ratio of opening areas on the leeward and the windward sides.

$$Q = 0.31 \times A_w \times V_m \times F \qquad \text{(Eqn. 1)}$$

where Q is the ventilation rate, CFM.

A_w is the area of openings on the windward sides, square feet. (Openings on walls parallel to the direction of the approach air stream should be taken as leeward openings.)

V_m is the speed of the approach air stream (FPM) corresponding to the meteorological wind speed which is normally measured at 30 feet above the ground.

F is a Flow Correction Factor that gives the increment or decrement in flow due to unequal areas of the windward and leeward openings. Values of F are obtained from Figure 7. (This data may not be extrapolated.)

Equation (1) has the same form as that given in the ASHRAE Handbook of Fundamentals for estimating wind ventilation in general type buildings. However, there are considerable differences in the ventilation rates predicted by these two equations, especially for perpendicular winds. Equation (1) is also free from the ambiguities that arise during the application of the ASHRAE equation.

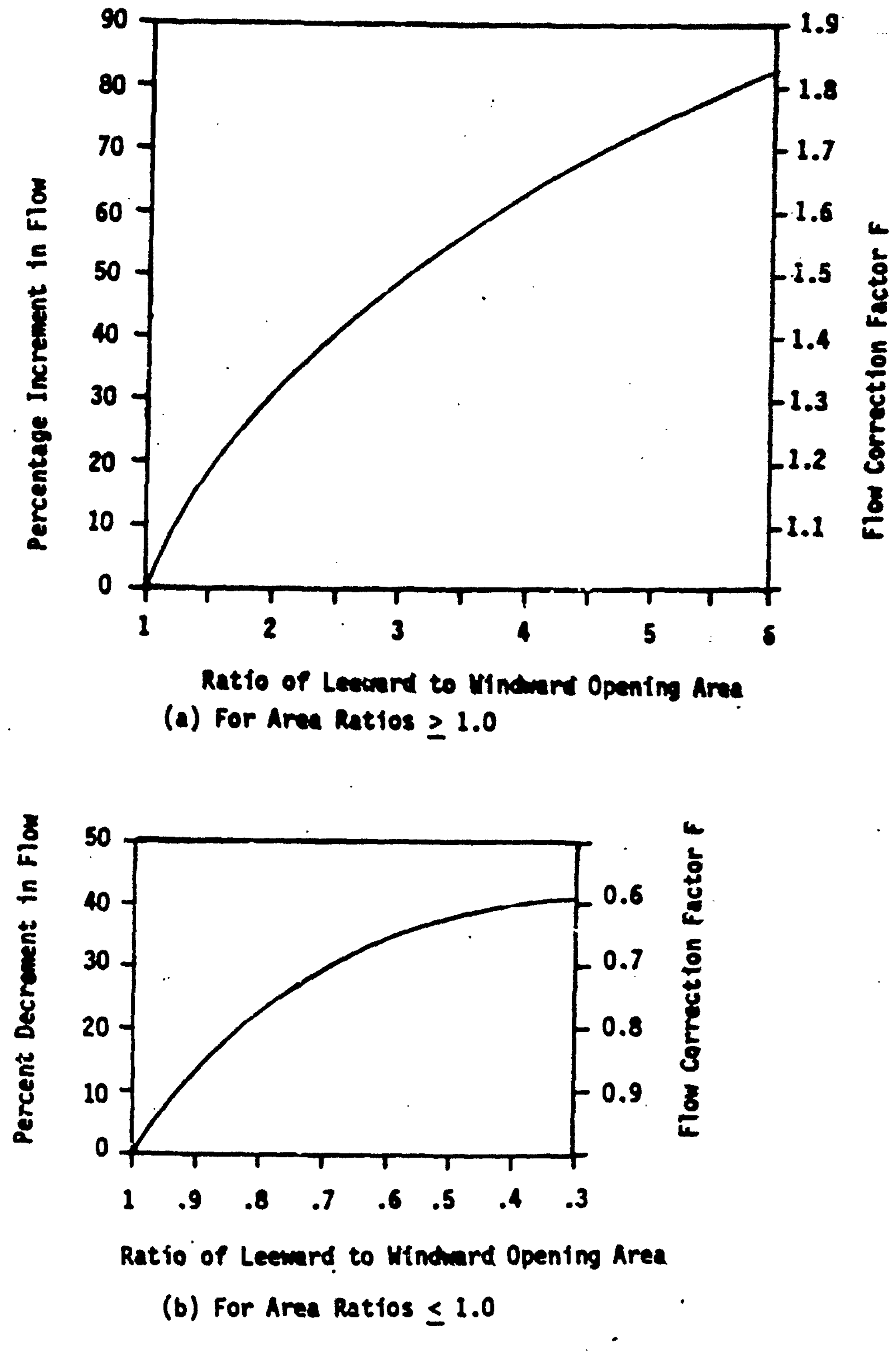

Figure 7 FLOW CHANGE DUE TO UNEQUAL AREAS OF WINDWARD AND LEEWARD OPENINGS

Models with five different opening configurations were used in the present tests. Total opening areas of these models varied from 2.5% to 3.44% of wall surface area (3.13% to 4.3% of floor area). Projected results show that, for all five configurations, ventilation rates of 1 CFM per square foot of floor area can be achieved at approach wind speeds as low as 3.5 mph.

Test results also showed that the highest values of shelter ventilation rate per unit area of wall openings are achieved when the ratio of windward to total opening area lies between 0.3 and 0.6 (Figures 8-11). If this ratio of opening areas can be met at all wind directions (by proper distribution of openings over the walls), it follows that the shelter will have the highest ventilation rates per unit area of wall openings for all wind directions.

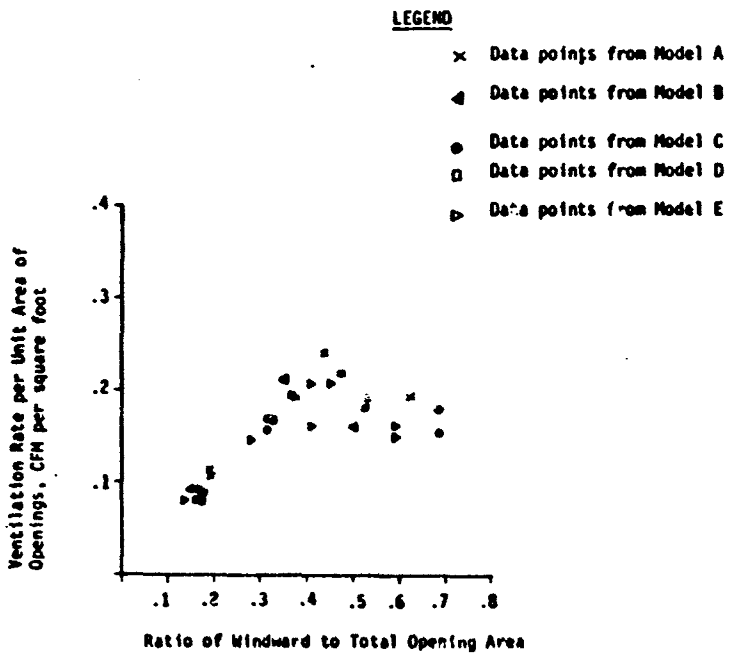

Figure 8 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 210 FPM

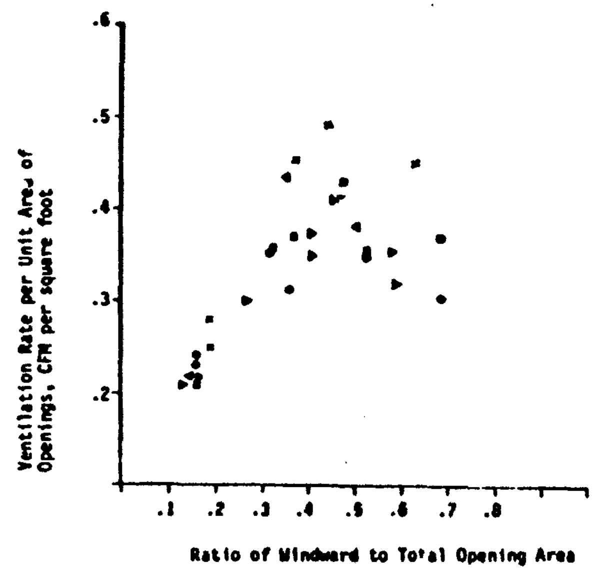

Figure 9 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 410 FPM

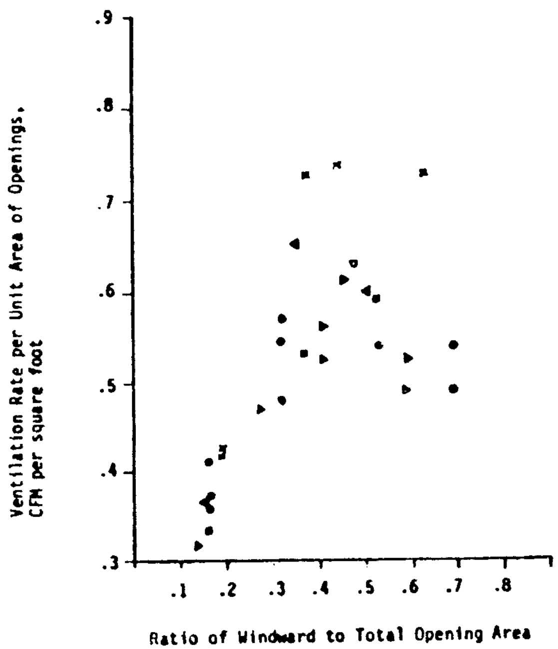

Figure 10 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 600 FPM

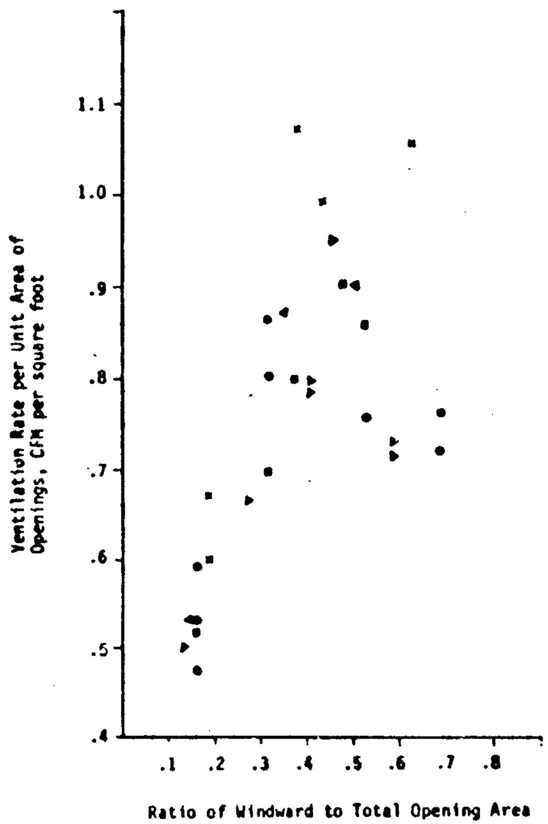

Figure 11 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 825 FPM

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Flow Visualization	Relative Wind Angle

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used, ~~in these tests~~. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas and the velocity of the approach wind.

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Results were compared with those projected from available correlations for general type buildings.

PREFACE

GARD, a Division of Chamberlain Manufacturing Corporation, has prepared this report for the Federal Emergency Management Agency (FEMA). Mr. Donald Bettge of FEMA served as Project Officer during the entire program.

This report details the work completed during the third year (Option 2) of a multiyear Shelter Ventilation Analysis Program. During the third year, an extensive experimental study was carried out to determine a correlation between the dependent variable, the shelter ventilation rate, and the independent variables influencing it. The independent variables analyzed include:

(i) Total area of wall openings
(ii) Area ratio of leeward to windward wall openings
(iii) Speed of approach wind and the
(iv) Relative wind angle.

Individuals at GARD who participated in this program include:

R.H. Henninger	-	Project Manager
Dr. S.F. Fields	-	Experimental Modeling
Dr. C.K. Krishnakumar	-	Experimental Modeling & Data Reduction
C.K. Schafer	-	Experimental Modeling & Data Reduction

GARD wishes to thank Mr. Bettge and FEMA for giving the opportunity to undertake this study.

Respectfully submitted,

R. H. Henninger, P.E.
Manager, Energy
Applications

Approved by:

P. A. Saigh, P.E.
Director, Government Programs

ABSTRACT

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used in these tests. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas and the velocity of the approach wind.

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Section 1

INTRODUCTION

1.1 Background

A multi-year Shelter Ventilation Analysis Program is currently in progress at GARD. The goal of this program is to analyze wind-induced ventilation in both below-ground and above-ground shelters under different wind conditions, to suggest guidelines for shelter design and to recommend expedient methods of enhancing ventilation in those shelters. The analysis is performed by conducting scale model tests in a low speed wind tunnel. This report describes the results of the third year's (Option 2) effort.

During the first year of this program, the baseline wind-induced ventilation characteristics (air volume flow rate and distribution) for a single-room, upgraded, above-ground shelter were studied and established. Some preliminary tests were also conducted to evaluate the effectiveness of Flow Enhancement Devices (FEDs) placed near the entrance and exit openings of below-ground blast shelters in improving wind-induced ventilation. These tests strongly suggested the possibility of achieving acceptable levels of ventilation in below-ground shelters even at moderate wind speeds with properly designed FEDs. Results of the first year's work under the program have been published in the form of a project report (Ref. 1).

The second year of the program (Option 1) focused on quantitatively estimating the ventilation enhancement capabilities of innovatively designed FEDs applied to a below-ground blast shelter. Also as part of this study, a limited number of tests were conducted to estimate the influence of a neighboring upstream flow obstruction (namely, a small building) on the ventilation throughput of the shelter. Results of the Option 1 study have been published in the form of a project report dated December, 1983 (Ref. 2).

Under Option 2 (the third year of the program), an extensive series of model tests were conducted to obtain correlations between the total area of exterior wall openings and the ventilation throughput of a bermed, above-ground fallout shelter and to estimate the influence of such important geometric variables as the ratio of the windward opening area to the leeward opening area. In these tests, the ratio of wall opening area to wall surface area was varied from about 2.5% to 3.5%. The distribution of door and window openings was also varied to generate five different shelter configurations. Model tests were conducted over the entire range of relative wind angles (0° to 360°) and the free stream air speed in the tunnel was varied from about 4 fps to 20 fps.

1.2 Objectives

The overall goal of this study program is to obtain a clear understanding of the complex problem of ventilation in above-ground fallout shelters with and without internal partitions and in below-ground keyworker shelters so that the ventilation throughput and the air distribution can be predicted and practical recommendations made to improve them. The specific objectives of the present study (Option 2) are:

- to determine a correlation between the total area of exterior wall openings and ventilation throughput in a bermed, above-ground fallout shelter
- to estimate the influence of the ratio of opening area on the windward side to that on the leeward side on shelter ventilation throughput.

1.3 Review of Literature

Extensive experimental and analytical studies of natural ventilation in full-scale above-ground fallout shelters were conducted by the Defense Civil Preparedness Agency (DCPA) in the 1960s. These studies utilized a relationship similar to the one given in the 1977 ASHRAE Handbook of Fundamentals (Ref. 3, Chapter 21) for estimating wind-induced ventilation in buildings:

$$Q = EAV$$

where Q = Air volume flow rate (cfm)

E = Effectiveness factor

A = Free area of inlets or outlets whichever is smaller (square feet)

V = Wind speed (feet per minute)

The value of the effectiveness factor varies from 0.5 to 0.6 for perpendicular winds and from 0.25 to 0.35 for winds at other angles. When the inlet and outlet areas are not equal, the flow increases in a nonlinear fashion with the area ratio (Figure 12, Chapter 21 of Ref. 3). The ASHRAE model is very crude and gives results that differ considerably from experimental values as indicated by the tests on full-scale buildings conducted by DCPA (Ref. 4-7) and the wind tunnel tests on scale models of fallout shelters conducted for the Federal Emergency Management Agency (Ref. 1). At the present time, established data are not available to predict quantitatively the influence of the earth berms on pressure distributions in the vicinity of the wall openings or the resulting ventilation rates through them.

1.4 Method of Approach

The approach taken to achieve the stated objectives consisted of several series of wind tunnel tests using a scale model of the fallout shelter studied in the basic program. The total area of wall openings and their distribution over the walls were varied and the model ventilation rates were measured over a wide range of approach wind speeds and relative wind angles. (Details of the experiments are described in Section 2.) Ventilation rates for the full-scale shelter were then projected from the model results using scaling laws.

Section 2

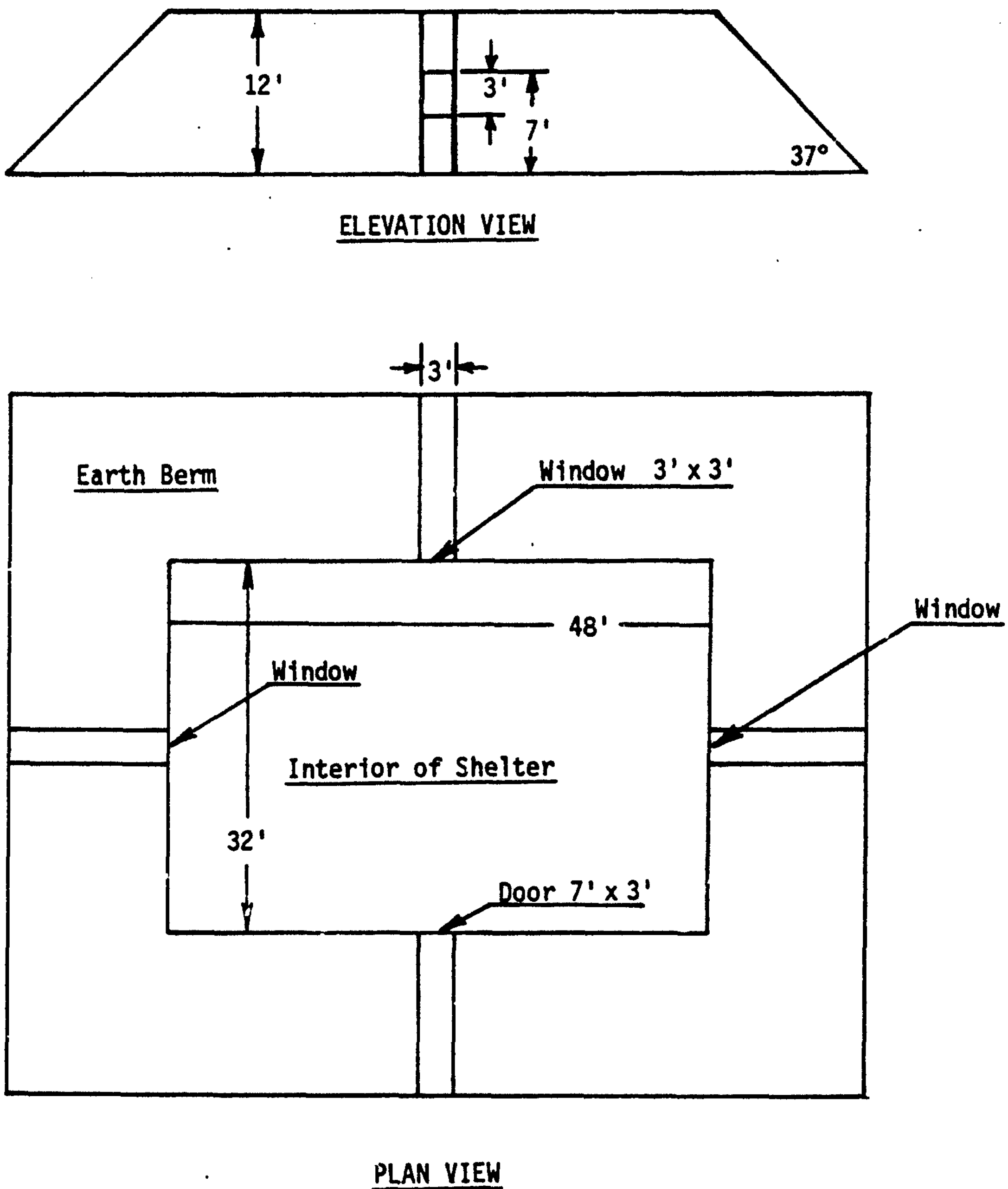
MODEL TESTING PROCEDURES

Fallout shelters with five distinct opening configurations were modeled in this study. All shelters had the same length (48 feet), width (32 feet) and height (12 feet) as the one studied in the first year program. However, the total area of the openings varied from 2.5% to 3.44% of the exterior wall surface. Opening distribution patterns were also varied. Figures 2.1-2.5 show the geometric details of each shelter configuration tested. For convenience, the shelters are labelled A through E as indicated.

2.1 Model Fabrication

Since all five shelters had the same overall dimensions, the different opening configurations were obtained from the same basic model by using close-fitting aluminum wedges and plates to block off, open up or modify one or more of the openings. Figures 2.6 and 2.7 show the basic model and the aluminum wedges. The length scale used was 1:36 (model:full-scale). Walls and earth berms of the model were fabricated from 3/16 inch thick aluminum plates and tempered glass sheets. The roof was made of 1/4 inch thick aluminum plate. All the plates and the wedges were machined to close tolerances to minimize errors due to air leakage. A 1/32 inch thick clear Plexiglass sheet, screwed to the bottom of the frame served as the shelter floor. Lines parallel to the walls were scribed on the Plexiglass sheet 3/16 inch apart on either side of each wall opening to serve as distance markers.

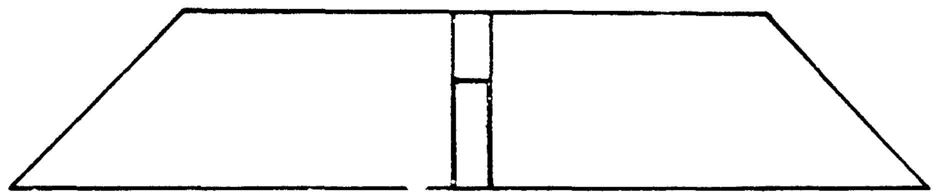
Six, 300 watt photographic lights were encased inside the simulated earth berms to illuminate the interior of the shelter model. The intensity of these lights could be controlled through a voltage regulator. These lights



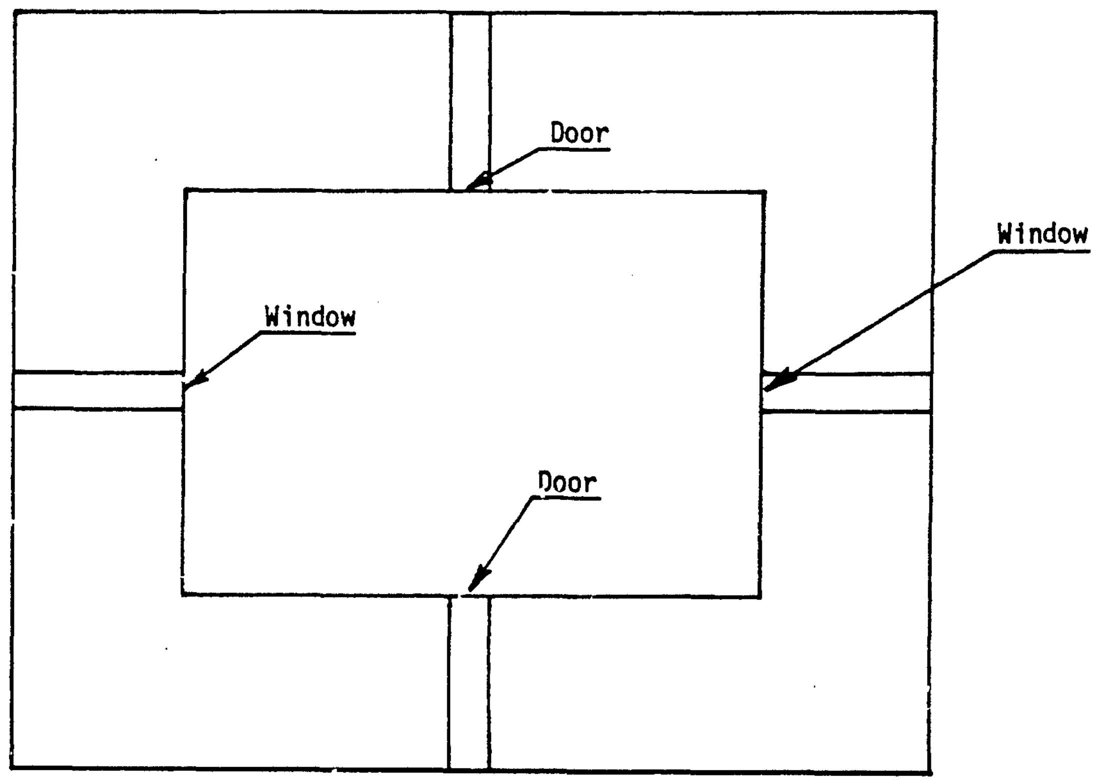
Ratio of opening area to wall surface area = 0.0250

Ratio of opening area to shelter floor area = 0.0313

Figure 2.1 SHELTER CONFIGURATION - A



ELEVATION VIEW

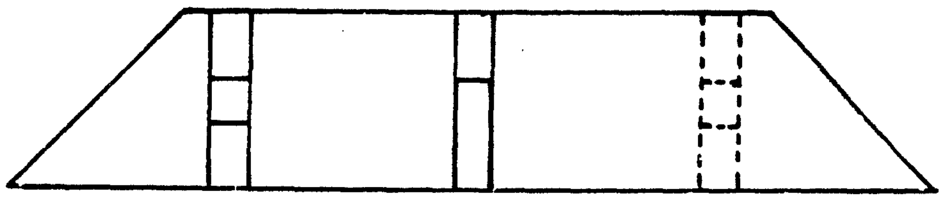


PLAN VIEW

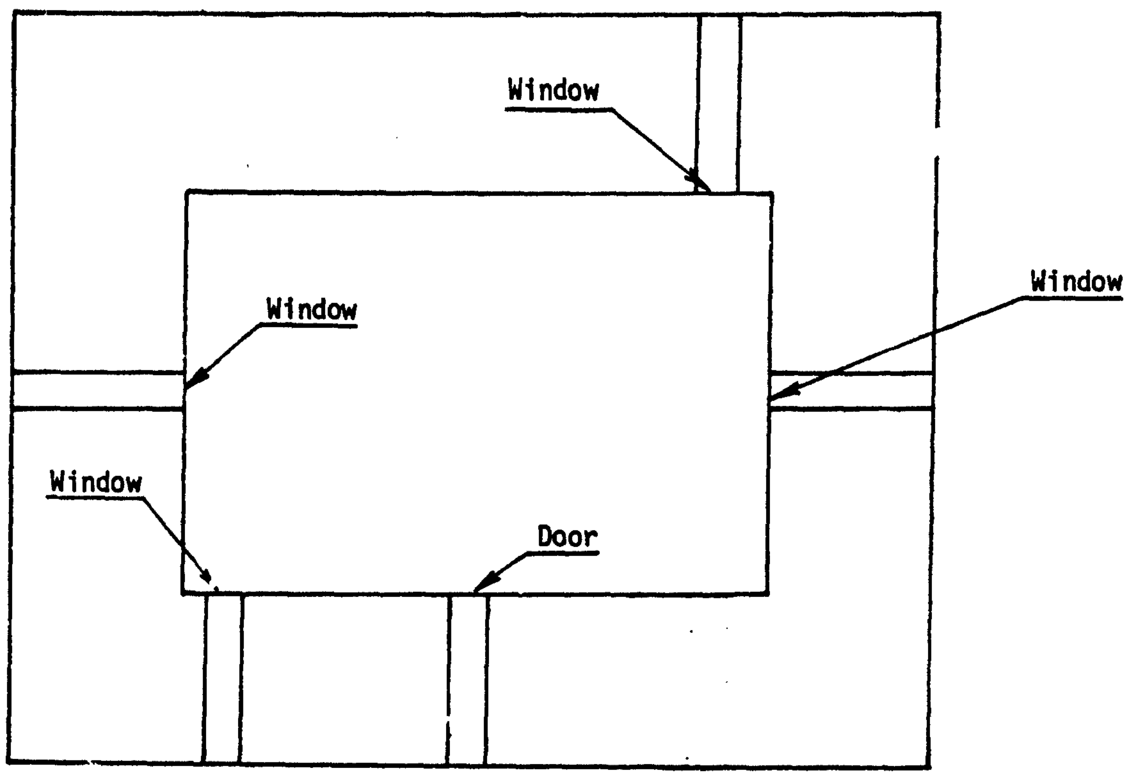
Ratio of opening area to wall surface area = 0.0313

Ratio of opening area to shelter floor area = 0.0391

Figure 2.2 SHELTER CONFIGURATION - B



ELEVATION VIEW

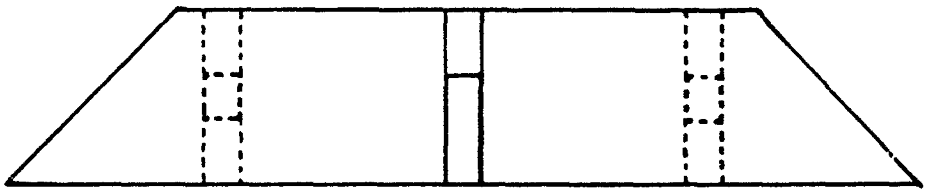


PLAN VIEW

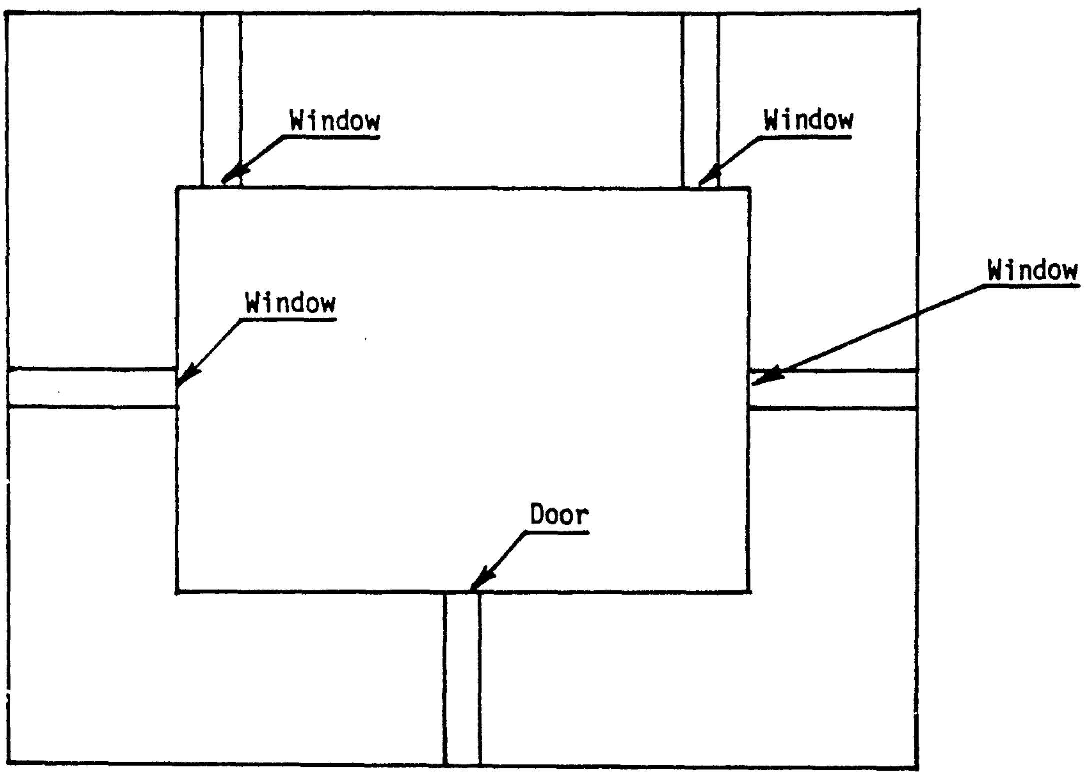
Ratio of opening area to wall surface area = 0.0297

Ratio of opening area to shelter floor area = 0.0371

Figure 2.3 SHELTER CONFIGURATION - C



ELEVATION VIEW

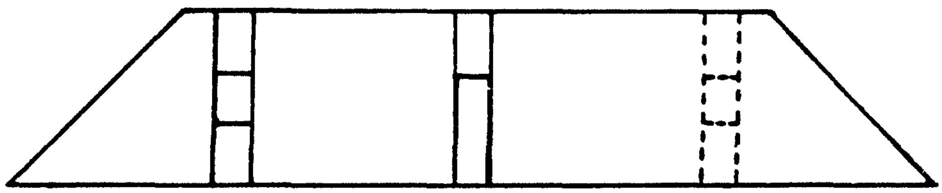


PLAN VIEW

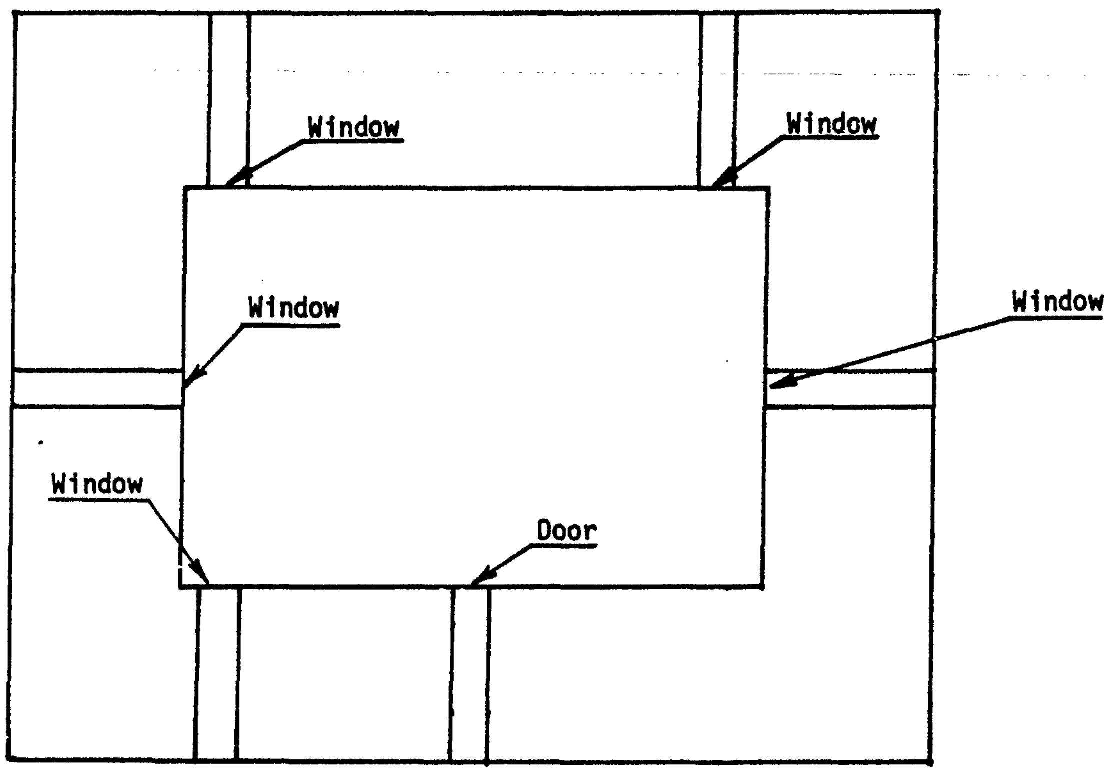
Ratio of opening area to wall surface area = 0.0297

Ratio of opening area to shelter floor area = 0.0371

Figure 2.4 SHELTER CONFIGURATION - D



ELEVATION VIEW



PLAN VIEW

Ratio of opening area to wall surface area = 0.0344

Ratio of opening area to shelter floor area = 0.0430

Figure 2.5 SHELTER CONFIGURATION - E

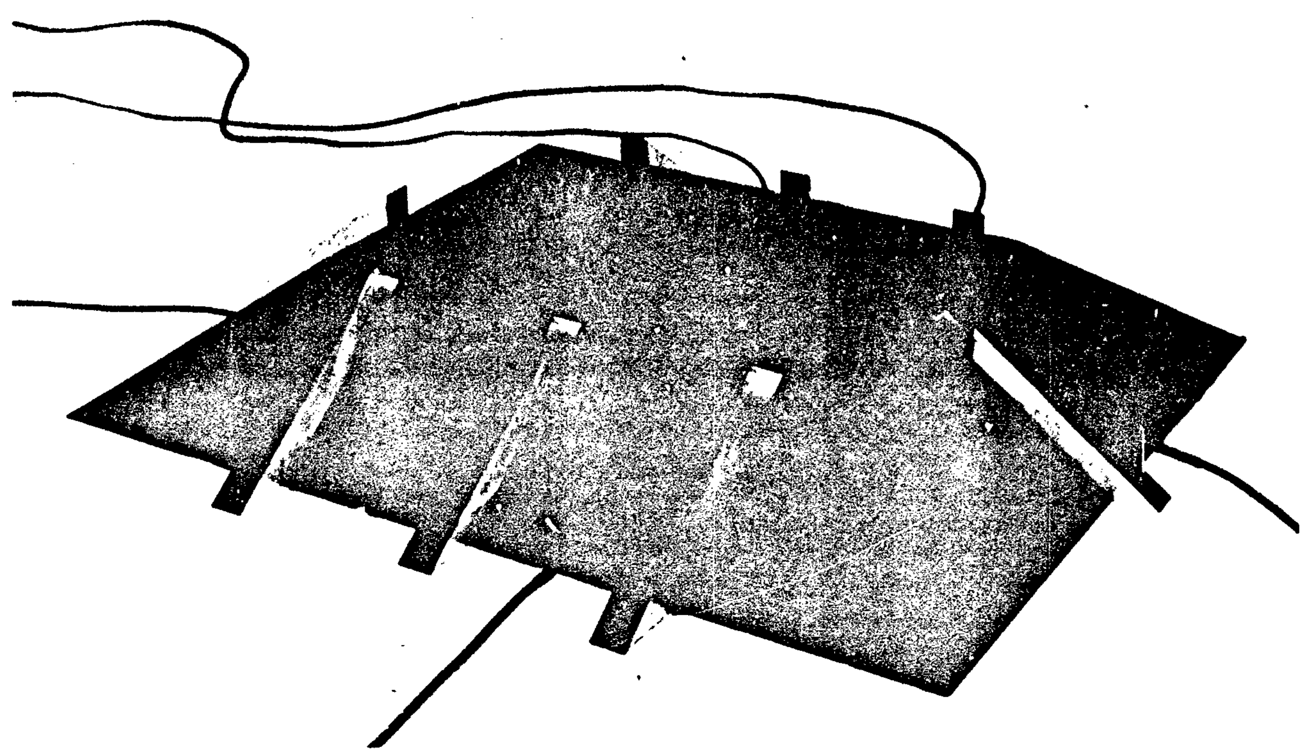


Figure 2.6 SHELTER MODEL WITH WEDGES PARTIALLY PULLED OLT

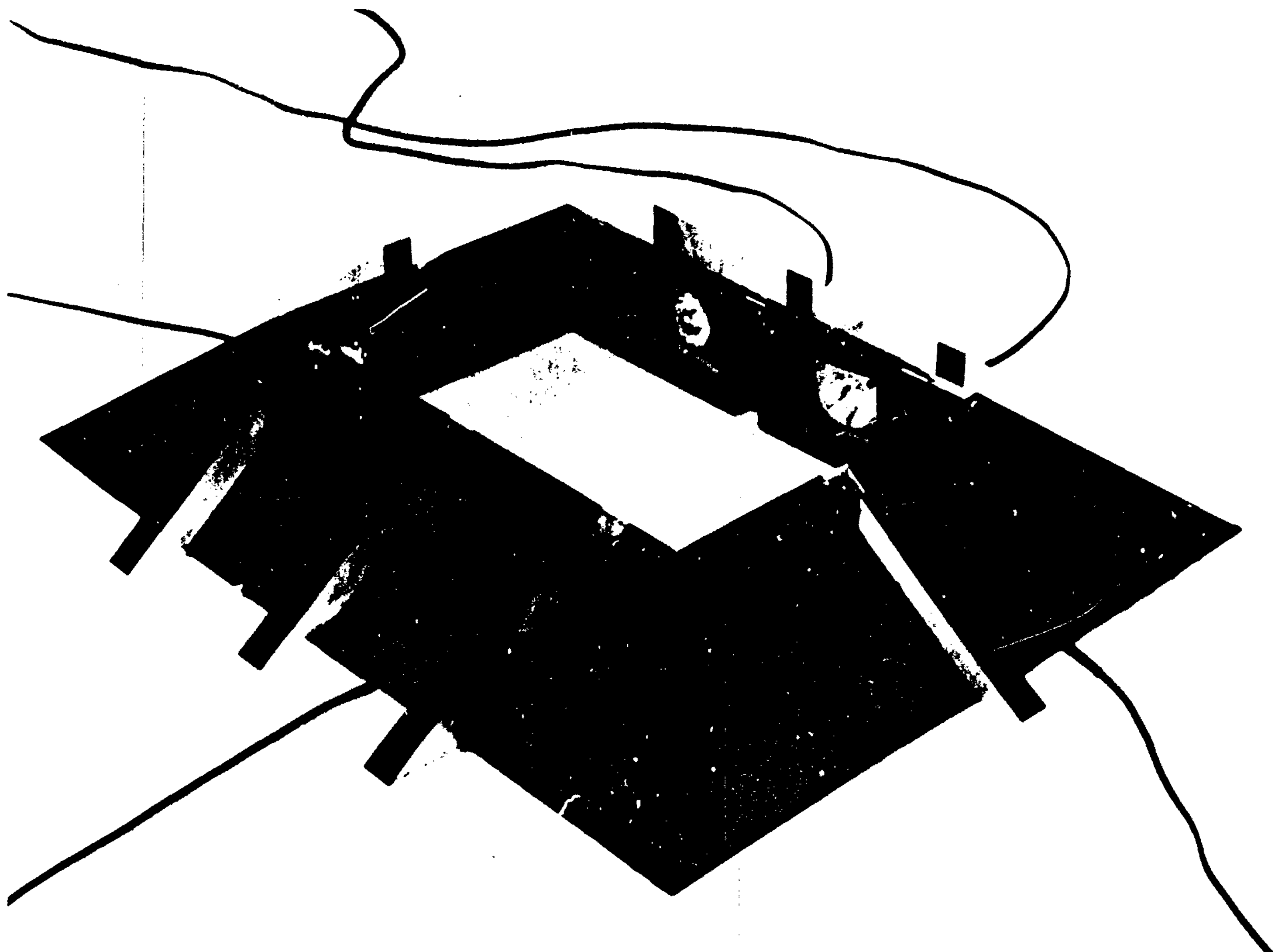


Figure 2.7 SHELTER MODEL WITH ROOF REMOVED

provided sufficient illumination to photograph the tracer bubt es and the scribe lines on the Plexiglass sheet. Figures 2.8-2.12 show the interior of the shelter model (roof removed).

2.2 Test Method

The method of testing used in this study was similar to the one used in Reference 2. First, a set of preliminary tests were made to calibrate the tunnel as described in Reference 1. These tests established a velocity profile in the tunnel's boundary layer that conformed to a power law distribution given by $V_1/V_2 = (Y_1/Y_2)^{1/3.35}$ where V_1 and V_2 are the velocities at heights of Y_1 and Y_2 respectively from the tunnel's floor*. This distribution was valid up to a height of approximately 18 inches from the tunnel's floor.

After establishing the desired velocity profile for the approach air stream, the following four test series were performed to determine model ventilation rates at each value of the approach air stream velocity:

1) Test Series 1 - Amemometer calibration for volume flow rate,
2) Test Series 2 - Determination of air flow rates with tubes at the leeward openings,
3) Test Series 3 - Determination of average flow velocities through the main windward openings with tubes at leeward openings,

*The exponent 1/3.35 corresponds to those recommended for wind velocity profiles in suburbs of cities (Ref. 8).

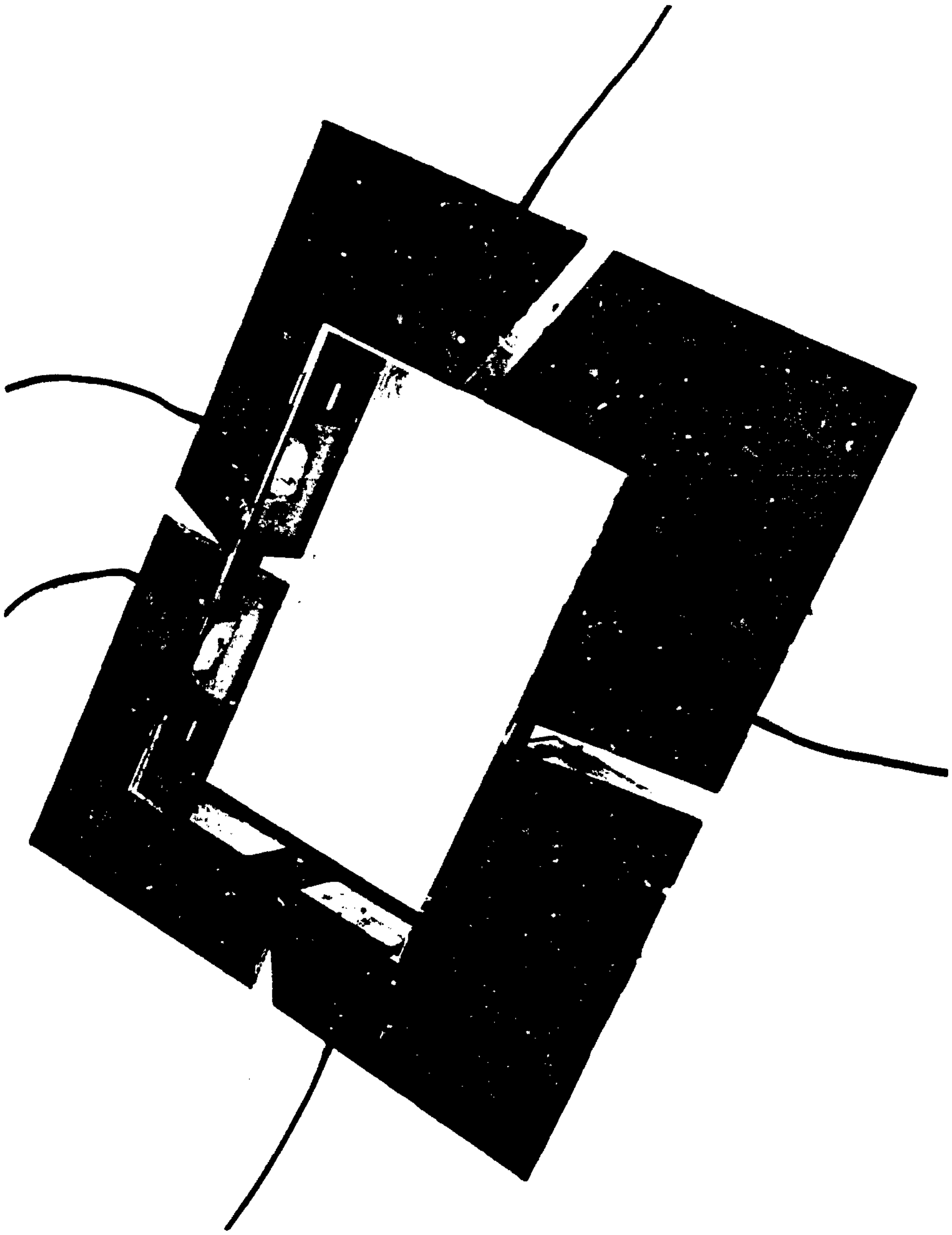


Figure 2.8 MODEL CONFIGURATION - A

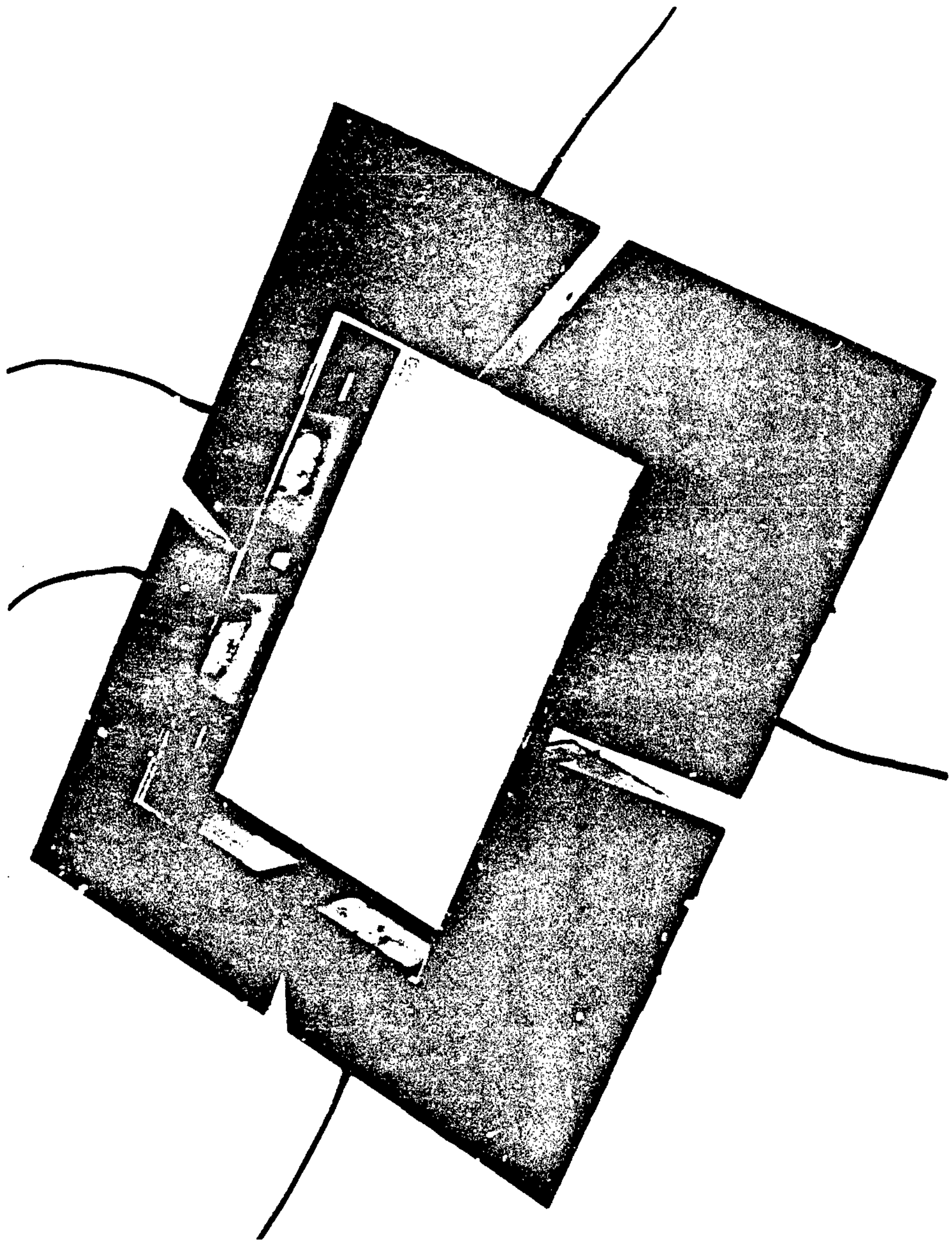


Figure 2.9 MODEL CONFIGURATION - B

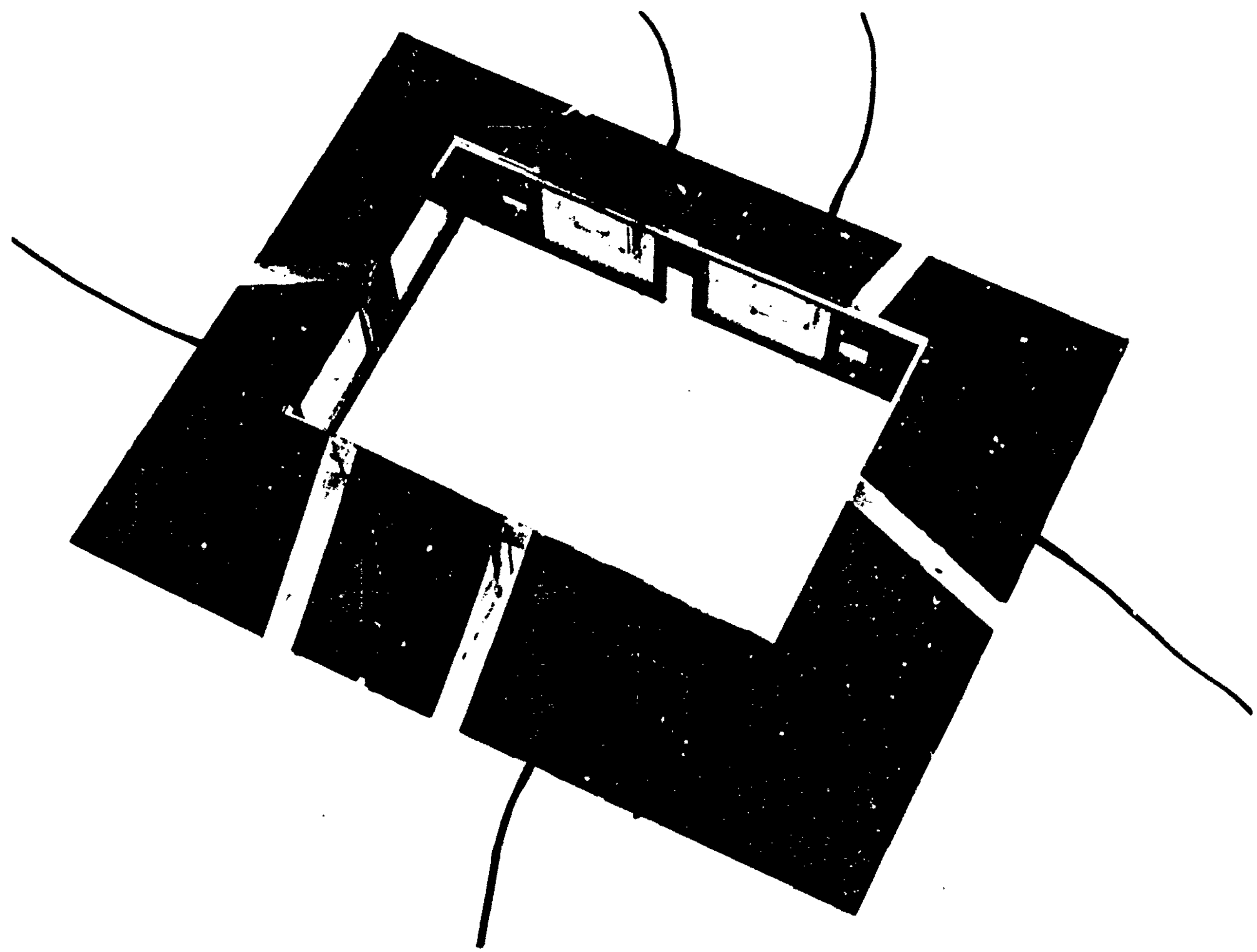


Figure 2.10 MODEL CONFIGURATION - C

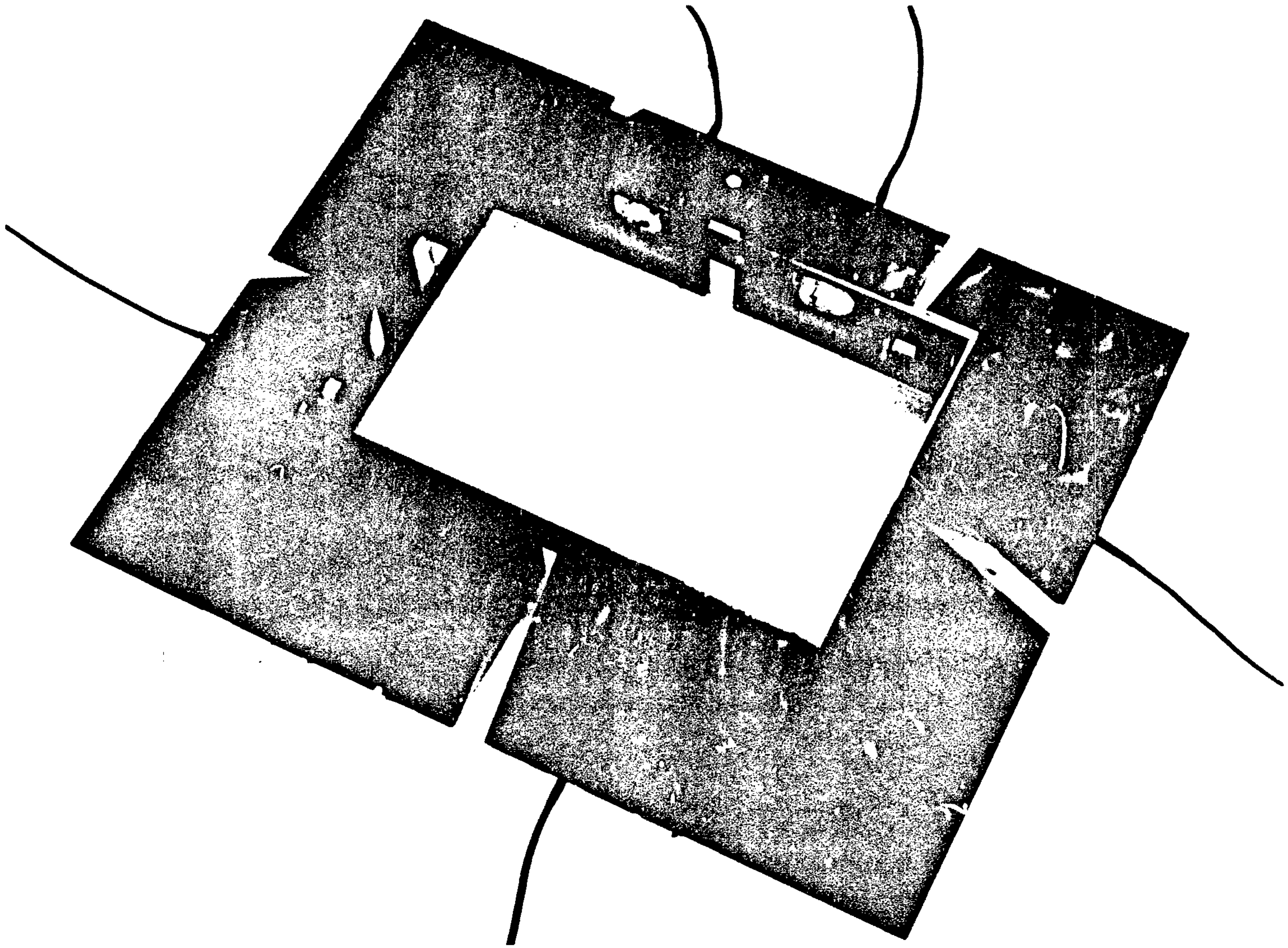


Figure 2.11 MODEL CONFIGURATION - D

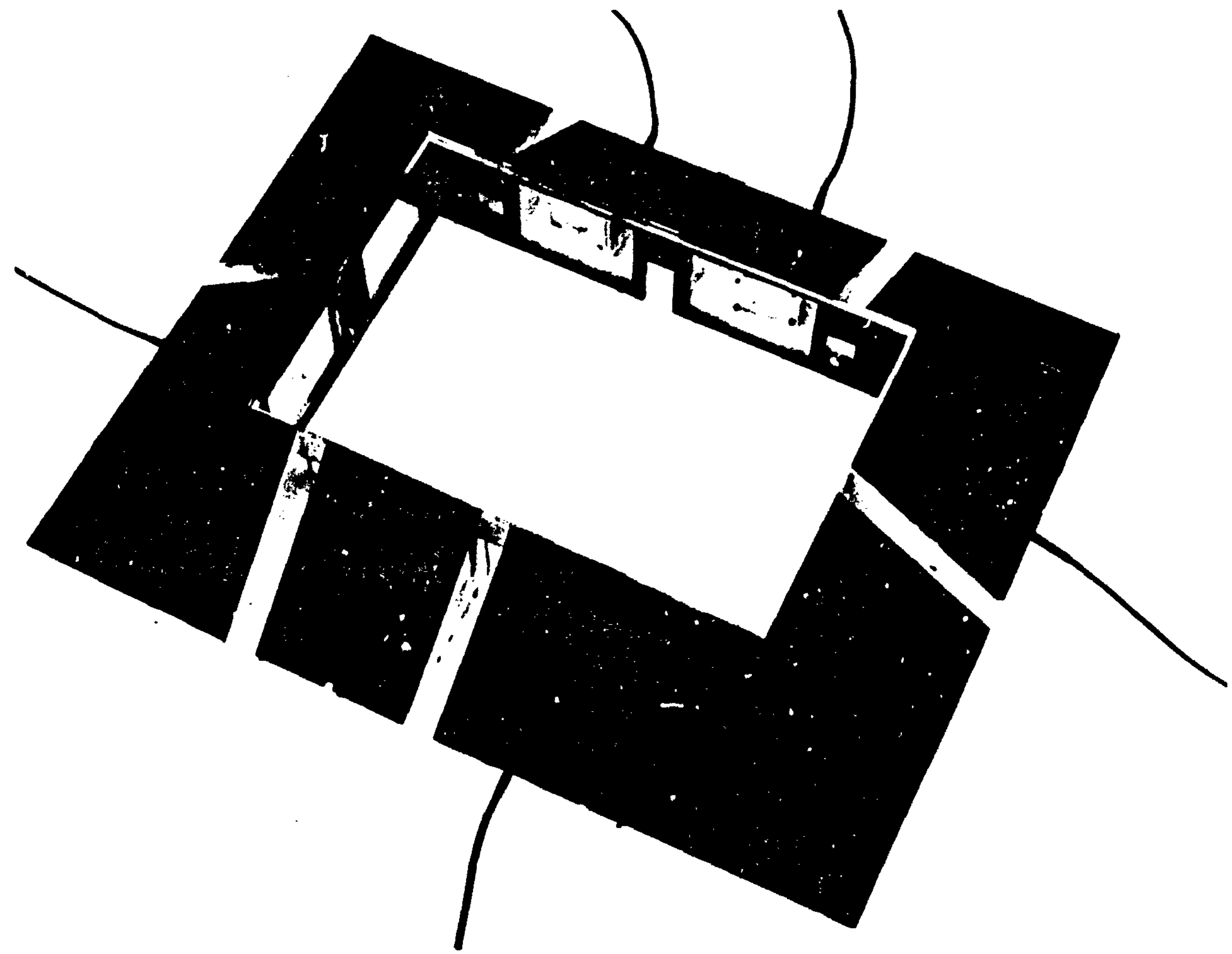


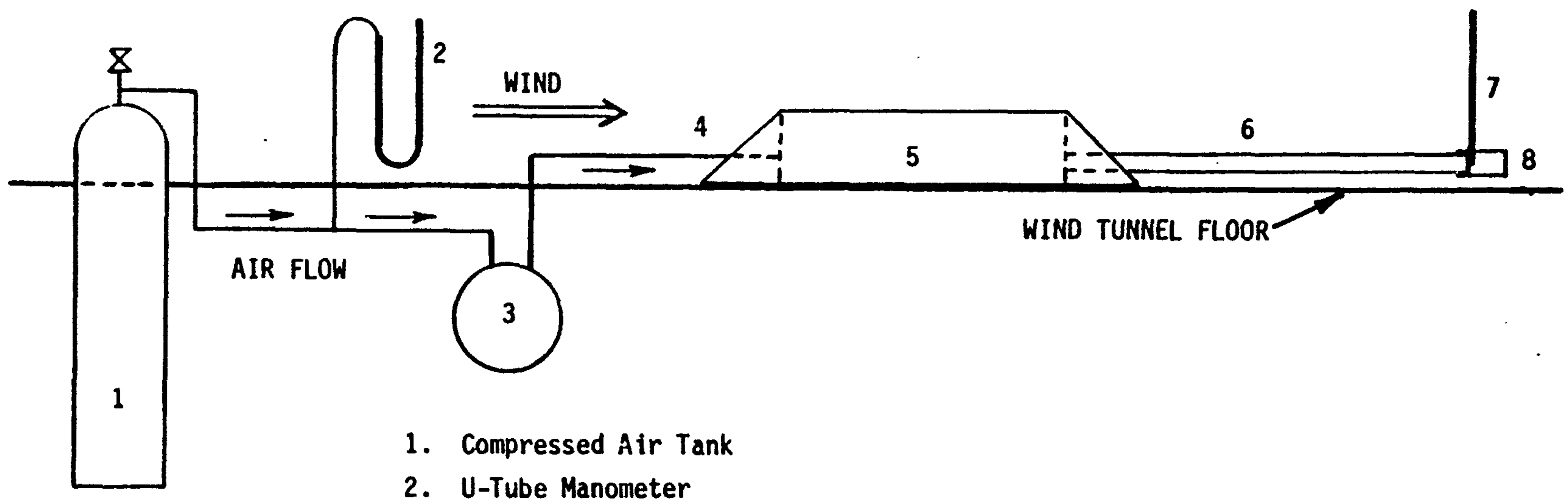
Figure 2.12 MODEL CONFIGURATION - E

4) Test Series 4 - Determination of average flow velocities through the main windward opening without tubes at leeward openings.

In the first series of tests, air volume flow rates through calibration tubes attached to leeward openings of the models were correlated with measurements of axial velocities at a section 15 diameters downstream of the leading edge of these tubes. This was done by forcing metered volume flow rates of air through one of the wall openings of the shelter and simultaneously recording anemometer readings of air flow velocities in the tube. In the second series of tests, actual values of ventilation rates through the model with tubes attached to the leeward openings were determined for different velocities of the approach air stream. Test Series 3 and 4 were performed to determine the "tube correction factor" which is defined as the factor by which the ventilation rates with the tubes (obtained from Test Series 2) should be multiplied to get actual values of model ventilation rates.

2.2.1 Test Series 1 - Anemometer Calibration for Volume Flow Rate

The object of these tests was to establish a correlation between the actual air volume flow rates through the shelter model and the axial velocity measurements of a Datamatrics hot-wire anemometer located at the exit planes of calibration tubes leading from the leeward openings. Figures 2.13 shows a schematic of the calibration test setup. The outer diameter of the calibration tube was 1 inch and the inner diameter was 7/8 inch. The tube had a length of 14 inches. The leading edge of the tube was pushed through a leeward wall opening of the shelter and through a one inch circular hole in a thin metal plate that was taped to the inside surface of the wall. Silicone rubber sealant was applied to prevent air leaks around the calibration tube and the



1. Compressed Air Tank
2. U-Tube Manometer
3. Sprangue Wet Test Gas Meter
4. Flexible Air Intake Tube
5. Shelter Model
6. Calibration Tube
7. Hot-Wire Anemometer Probe
8. Extension Tube

Figure 2.13 SETUP FOR ANEMOMETER CALIBRATION opening in the plate. The anemometer probe was positioned at the rear end of the calibration tube with its sensor at the tube axis. A short piece of extension tube with a slot to permit passage of the anemometer probe was attached to the rear end of the calibration tube as shown. All other wall openings except one on the windward side were sealed tight. A flexible air intake tube was attached to this opening and the gaps around the tube and opening sealed with Silicone rubber sealant.

Air from a compressed air tank was admitted into the model at flow rates ranging from 0.1 cfm to 1.5 cfm and the corresponding readings of the anemometer were recorded. The actual volume flow rates were given by the gas flow meter which itself was calibrated by a separate volume flow displacement test. Next, the test was repeated for wind tunnel free stream speeds of 5 fps and 15 fps. Following this, the turn-table was rotated to set another value of approach wind angle (θ) and the tests repeated at the same two free stream speeds. Calibration tests were performed at relative wind angles of 0°, 30° and 45°. It was observed that the correlation between the actual air volume flow rate through the model and the anemometer reading was not significantly affected by the speed and direction of the approach air stream in the range tested. The correlation is given in Figure 2.14.

Additional calibration tubes were attached to the remaining leeward openings and the calibration tests repeated. Anemometer readings for each of the leeward tubes were recorded for different air supply rates through the windward intake tube. It was established that air volume flow rates through the model could be obtained as the sum of the flow rates through the individual calibration tubes which in turn were obtained from the respective anemometer readings and the correlation curve of Figure 2.14.

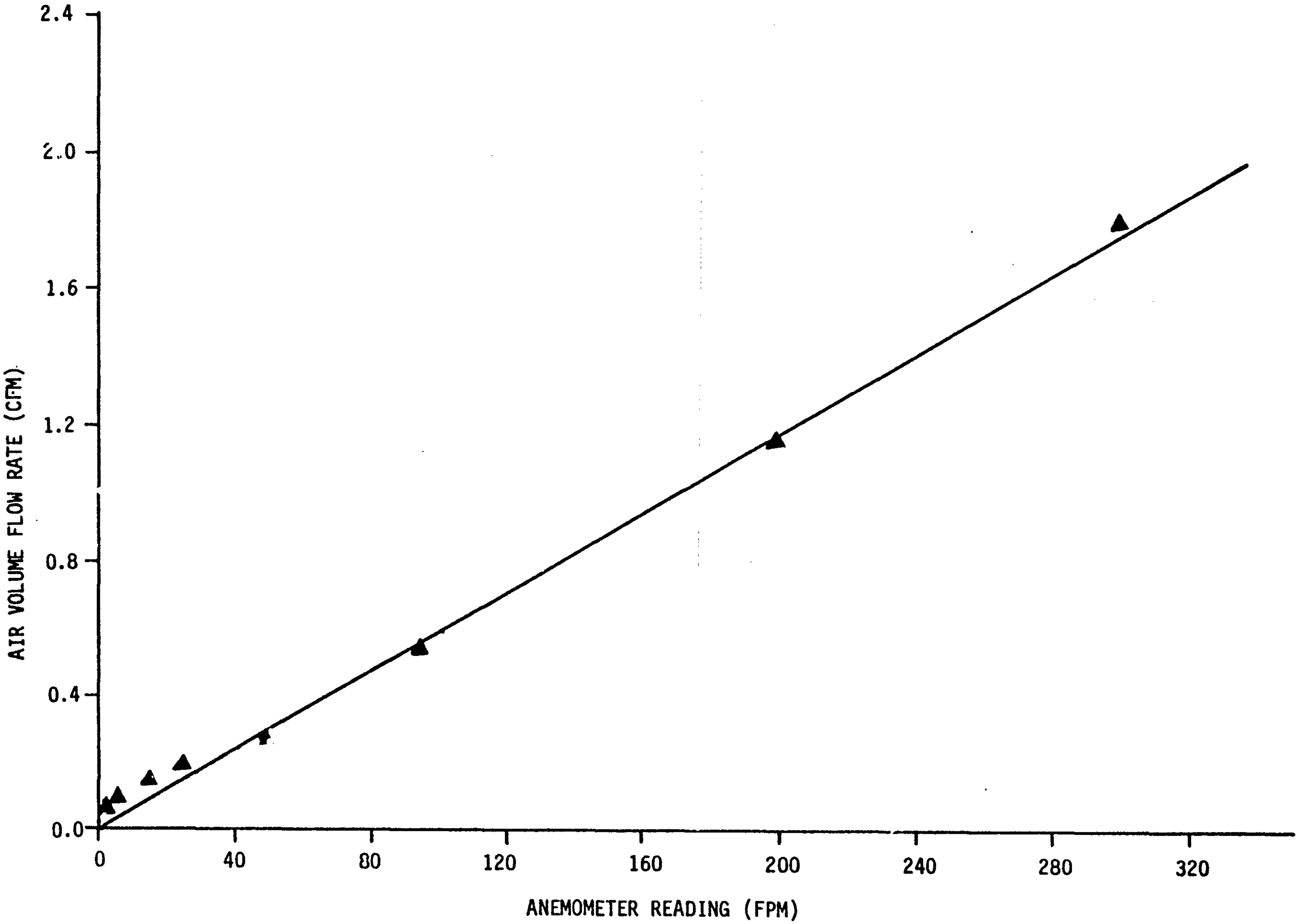


Figure 2.14 ANEMOMETER CALIBRATION CURVE

2.2.2 Test Series 2 - Determination of Air Volume Flow Rates With Tubes at Leeward Openings

In this series of tests, actual air volume flow rates through the shelter models with calibration tubes attached to the leeward openings were determined for various approach wind speeds and relative wind angles. Values of the air volume flow rates were obtained from measurement of axial velocities in each of the leeward tubes and the calibration curve of Figure 2.14. Approach wind speeds (V_m) in the tunnel* were varied from 3.5 fps to 13.75 fps. The direction of the approach stream relative to the main axis of the shelter (defined as the relative wind angle θ, Figure 2.15), was varied over the full range of 0° to 360°. Models A and D are symmetric with respect to their transverse axes. With these models, tests were made for relative wind angles of 0° through 180°. Model B is symmetric with respect to both the transverse and the longitudinal axes. For this model, the relative wind angle was varied only from 0° to 90°. Models C and E are not symmetric with respect to either the transverse or the longitudinal axis. Tests with these models were carried out over the entire range of 0° to 360°. In all, 116 tests were performed in Test Series 2. A typical test set-up is shouwn in Figure 2.16.

2.2.3 Test Series 3 - Determination of Average Bubble Velocity With Tubes at Leeward Openings

The object of the tests in Test Series 3 and 4 were to obtain values of the tube correction factor as a function of the approach wind condition. The

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*Approach wind speeds in this study were measured at a height of 10 inches above the tunnel floor. This corresponds to wind speeds at a full-scale height of 30 feet at which metereological wind speeds are normally reported.

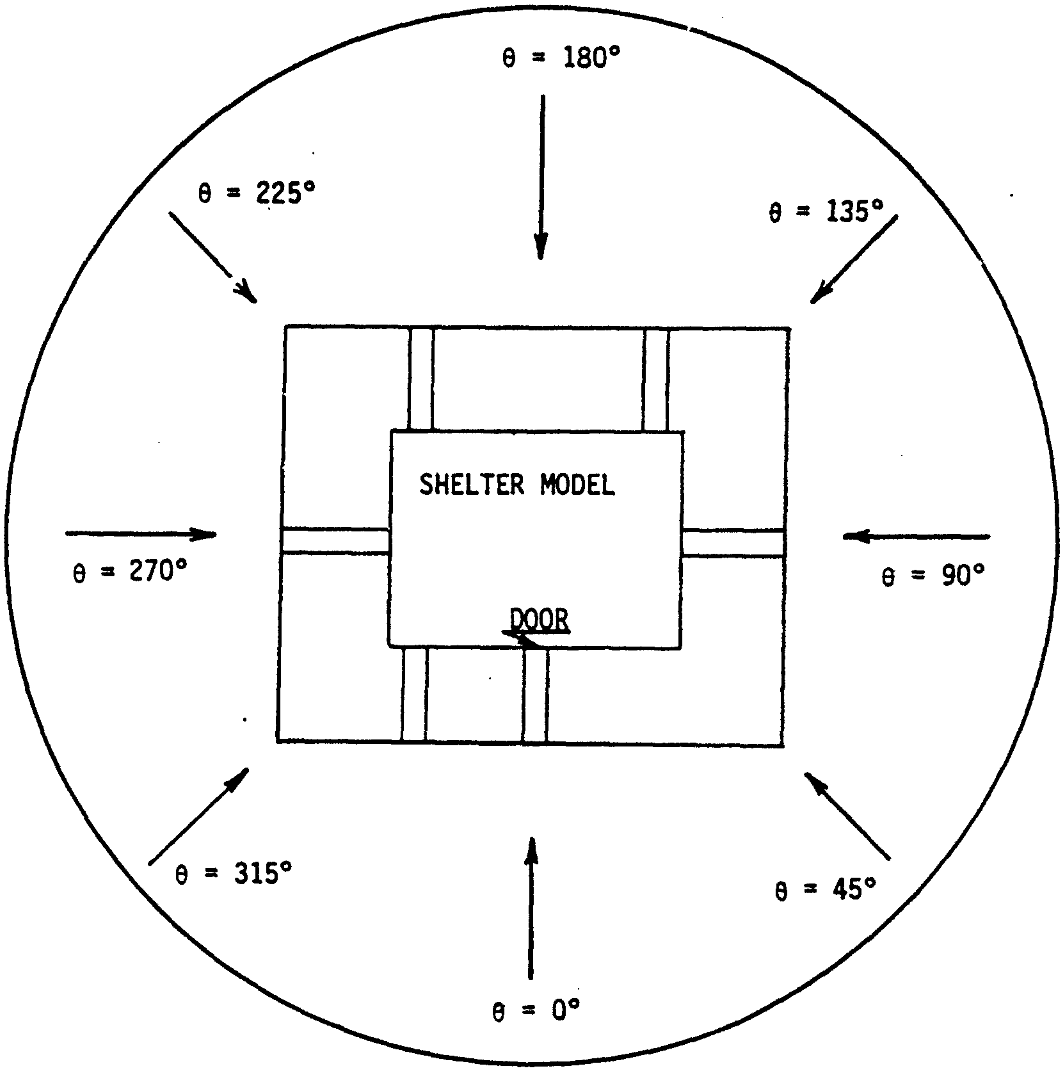

Figure 2.15 RELATIVE WIND ANGLES TESTED

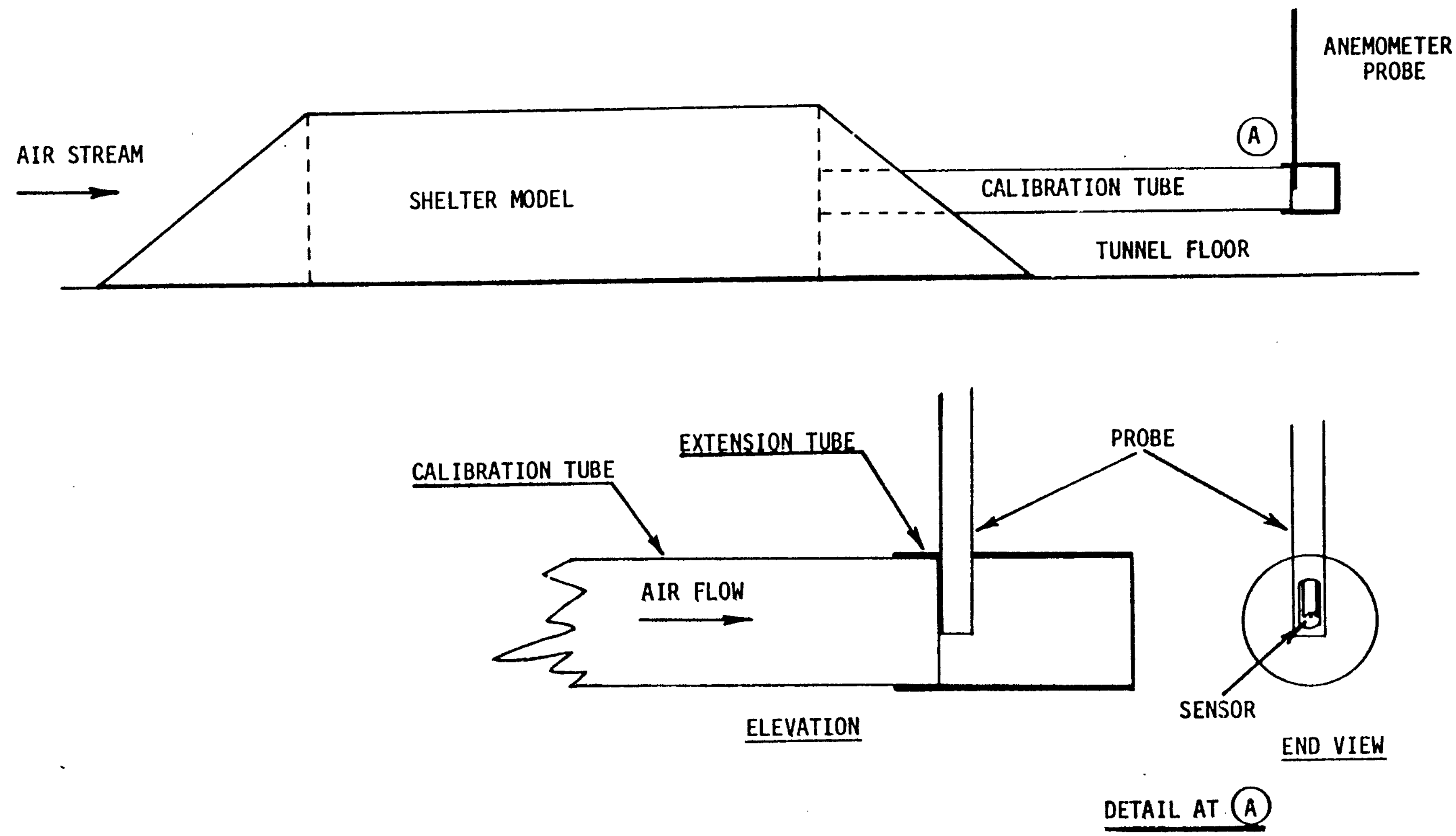

Figure 2.16 TYPICAL TEST SETUP FOR DETERMINATION OF AIR VOLUME FLOW RATES WITH TUBES AT LEEWARD OPENINGS

tube correction factor is a measure of the reduction in the model ventilation rate due to the presence of the calibration tubes at the leeward openings. It was calculated as the ratio of the average flow velocity at the main windward opening obtained without tubes at the leeward openings to that obtained when tubes were attached to the leeward openings. Average flow velocities through the main windward openings were obtained by determining the average velocities of tracer bubbles passing through them as described in the following pages.

Test Series 3 consisted of 58 tests in which average velocities of tracer bubbles passing through the main windward opening were determined for various speeds of the approach air stream and the relative wind angle θ. Figure 2.17 shows a photograph of a typical setup for recording bubble flow tracers entering the model. Calibration tubes were attached to all the leeward openings as described earlier. Tracer bubbles from the bubble generator (Ref. 1) were released at approximately 10 inches upstream of the model so as to get the desired level of bubble population entering the model. The 300 watt lights placed inside the shelter berms were turned on and their intensity adjusted to the desired level. Only those lights that were focused on the scribe lines at the windward openings were switched on. An additional 300 watt light was placed approximately 2 feet upstream of the model to shine on to the scribe lines upstream of the windward opening. The movie camera was focused on to the image of the windward wall opening reflected from the mirror placed below the wind tunnel. This mirrow was placed at an angle of 45° to the floor. It provided a convenient means of observing and recording flow patterns inside the shelter model.

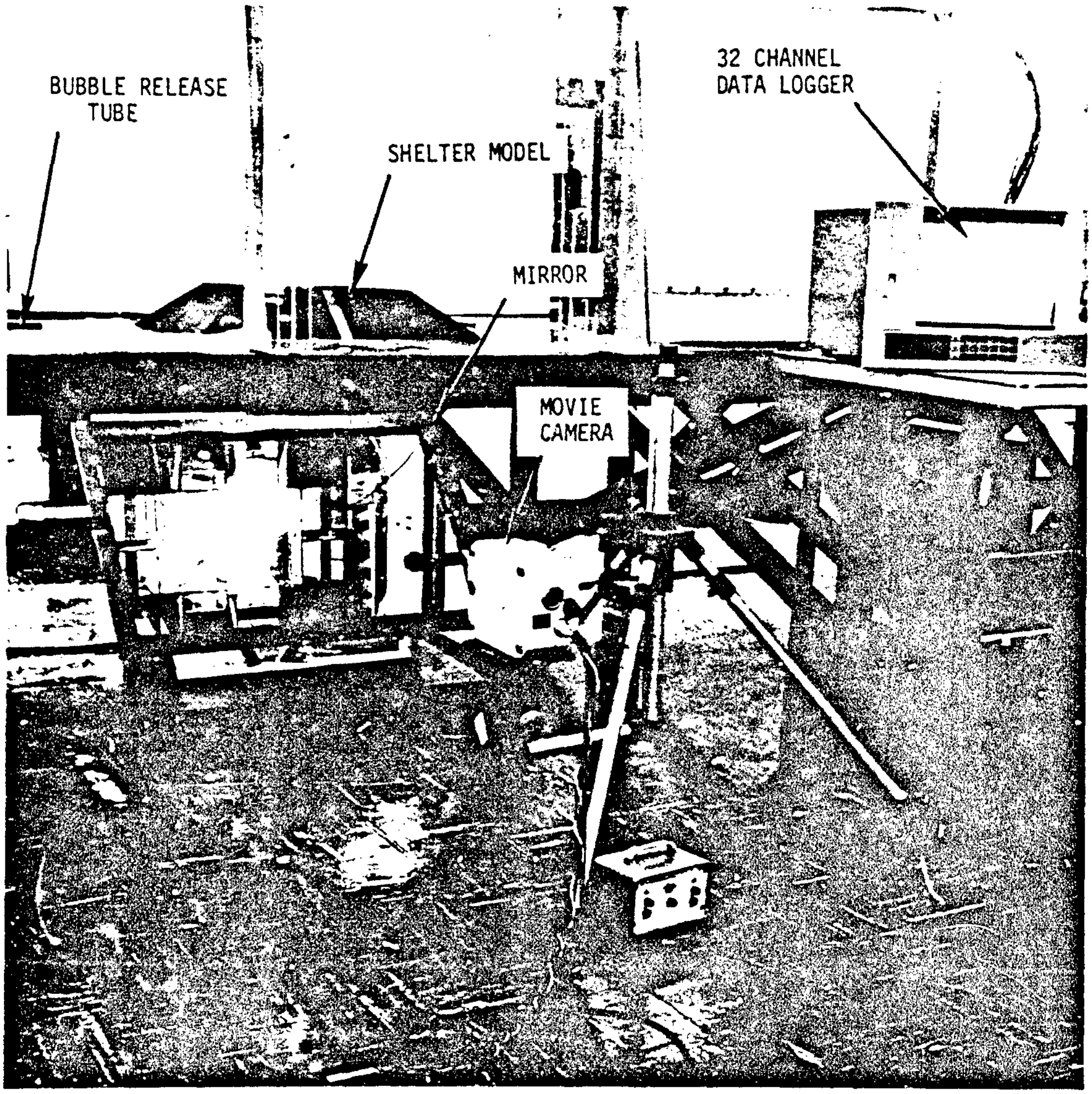

Figure 2.17 TEST SETUP FOR RECORDING FLOW TRACERS

For each value of the relative wind angle, tracer bubble flow was recorded for two values of the approach wind speed (V_m equal to 8 FPS and 12 FPS). The turn-table was then rotated to set another value of the relative wind angle. The new leeward openings were identified and calibration tubes were attached to them. Openings in walls which were parallel to the plane of the approach air stream (longitudinal axis of the tunnel) were identified as leeward openings. Net flow through these openings was always found to be outwards. The entire filming was done at a camera speed of 120 frames per second. The distance between adjacent scribe lines was 3/16 inch, also the thickness of the walls. The average velocity of a bubble normal to the plane of the wall opening was calculated as:

$$\text{Bubble velocity, } V_b \text{ (FPS)} = \frac{\text{Distance moved across the openings (inches) / 12 inches/foot}}{\text{Number of frames to move through the distance / 120 frames/second}}$$

The air flow velocity through the opening was taken as equal to the average velocity of 25 to 30 bubbles in each case.

2.2.4 Test Series 4 - Determination of Average Bubble Velocity Without Tubes at Leeward Openings

In this series of tests, average values of bubble flow velocities V_B through the main windward opening were determined without attaching calibration tubes to the leeward openings. The tests were similar to those of the previous series. With one of the shelter models (Model D), tests were made at two different values of approach wind speed (V_m equal to 8 FPS and 12 FPS) for θ equal to 0°, 45° and 135°. Using values of bubble velocities V_b from Test Series 3, values of the tube correction factor V_B/V_b for each of the three relative wind angles were calculated at both approach wind speeds (V_m equal to 8 FPS and 12 FPS). It was noted that the tube correction factor depended strongly on the relative wind angle. However, it was practically independent of the wind speed. Therefore, the remaining tests were conducted only at one value of the approach wind speed (V_m equal to 12 FPS). In all, 32 tests were performed under this series.

Section 3

PRESENTATION AND DISCUSSION OF RESULTS

3.1 Results of Model Testing

Air volume flow rates (Q_T) through the shelter models obtained with calibration tubes attached to the leeward openings (from Test Series 2) and the average bubble flow velocities through the main windward operings with and without calibration tubes at the leeward openings (from Test Series 3 and 4) are presented in Tables 3.1 - 3.5. These tables also give the tube correction factors and the model ventilation rates for the various approach wind speeds and relative wind angles. Based on these results, the following correlation was obtained between the dependent variable of model ventilation rate and the independent variables of approach wind velocity, windward opening area and a factor F whose value depends on the ratio of the leeward opening area to the windward opening area:

$$Q = 0.31 \times A_w \times V_m \times F \qquad \text{(Eqn. 1)}$$

where Q is the ventilation rate, CFM.

A_w is the area of openings on the windward sides, square feet. (Openings on walls parallel to the direction of the approach air stream should be taken as leeward openings.)

V_m is the speed of the approach air stream (FPM) corresponding to the meteorological wind speed which is normally measured at 30 feet above the ground.

TABLE 3.1
MEASURED VENTILATION RATES - SHELTER MODEL A

θ Relative Wind Angle (Deg.)	V_M Approach Wind Speed (FPM)	Q_T Ventilation Rate with Tubes in Place (CFM)	V_b Air Speed at Inlet Opening With Tubes in Place (FPS)	V_B Air Speed at Inlet Opening Without Tubes (FPS)	V_B/V_b Tube Correction Factor	Q Model Ventilation Rate (CFM)
0	210 410 600 825	0.99 2.04 3.04 4.09	3.75	4.84	1.29	1.28 2.63 3.92 5.28
45	210 410 600 825	0.71 1.65 2.68 3.97	3.21	4.78	1.45	1.03 2.39 3.89 5.76
90	210 410 600 825	0.50 1.21 1.99 2.87	4.90	5.44	1.11	0.56 1.34 2.21 3.19
135	210 410 600 825	0.62 1.48 2.35 3.48	3.03	5.44	1.63	1.01 2.41 3.85 5.67
180	210 410 600 825	0.57 1.40 2.10 3.30	4.64	4.99	1.08	0.62 1.51 2.27 3.56

$$Q = Q_T \left(\frac{V_B}{V_b}\right)$$

TABLE 3.2
MEASURED VENTILATION RATES - SHELTER MODEL B

θ Relative Wind Angle (Deg.)	V_M Approach Wind Speed (FPM)	Q_T Ventilation Rate with Tubes in Place (CFM)	V_b Air Speed at Inlet Opening With Tubes in Place (FPS)	V_B Air Speed at Inlet Opening Without Tubes (FPS)	V_B/V_b Tube Correction Factor	Q Model Ventilation Rate (CFM)
0	210 410 600 825	0.99 2.04 3.04 4.09	3.75	5.33	1.42	1.41 2.90 4.32 5.81
45	210 410 600 825	0.71 1.65 2.68 3.97	3.21	4.82	1.50	1.07 2.48 4.02 5.96
90	210 410 600 825	0.50 1.21 1.99 2.87	4.90	6.00	1.22	0.61 1.48 2.43 3.50

TABLE 3.3
MEASURED VENTILATION RATES - SHELTER MODEL C

θ Relative Wind Angle (Deg.)	V_M Approach Wind Speed (FPM)	Q_T Ventilation Rate with Tubes in Place (CFM)	V_b Air Speed at Inlet Opening With Tubes in Place (FPS)	V_B Air Speed at Inlet Opening Without Tubes (FPS)	V_B/V_b Tube Correction Factor	Q Model Ventilation Rate (CFM)
	210	1.13				1.20
0	410	2.10			1.06	2.23
	600	3.22				3.41
	825	4.51	4.08	4.32		4.78
	210	0.86				0.97
45	410	1.71			1.13	1.93
	600	2.74				3.10
	825	4.06	3.66	4.12		4.59
	210	0.48				0.50
90	410	1.39			1.04	1.45
	600	2.25				2.34
	825	3.25	5.52	5.74		3.38
	210	0.81				1.05
135	410	1.72			1.30	2.24
	600	2.75				3.58
	825	4.21	4.06	5.25		5.47
	210	0.54				0.58
180	410	1.28			1.07	1.37
	600	1.94				2.08
	825	2.80	5.60	6.00		3.00
	210	0.93				1.00
225	410	2.10			1.07	2.25
	600	3.24				3.47
	825	4.74	5.00	5.33		5.07
	210	0.48				0.56
270	410	1.31			1.16	1.52
	600	2.24				2.60
	825	3.22	5.18	5.99		3.74
	210	0.75				1.18
315	410	1.57			1.49	2.34
	600	2.27				3.38
	825	3.21	2.92	4.36		4.78

TABLE 3.4
MEASURED VENTILATION RATES - SHELTER MODEL D

θ Relative Wind Angle (Deg.)	V_M Approach Wind Speed (FPM)	Q_T Ventilation Rate with Tubes in Place (CFM)	V_b Air Speed at Inlet Opening with Tubes in Place (FPS)	V_B Air Speed at Inlet Opening without Tubes (FPS)	V_B/V_b Tube Correction Factor	Q Model Ventilation Rate (CFM)
0	210 410 600 825	1.20 2.31 3.31 4.95	5.71	5.80	1.02	1.22 2.36 3.38 5.05
45	210 410 600 825	0.99 1.95 3.19 4.62	3.70	4.34	1.17	1.16 2.28 3.73 5.41
90	210 410 600 825	0.52 1.34 2.11 3.25	5.60	5.60	1.00	0.52 1.34 2.11 3.25
135	210 410 600 825	0.87 1.72 2.54 3.62	4.05	6.39	1.58	1.37 2.72 4.01 5.72
180	210 410 600 825	0.90 1.78 2.57 3.74	4.63	5.44	1.18	1.06 2.10 3.03 4.41

TABLE 3.5
MEASURED VENTILATION RATES - SHELTER MODEL E

θ Relative Wind Angle (Deg.)	V_M Approach Wind Speed (FPM)	Q_T Ventilation Rate with Tubes in Place (CFM)	V_b Air Speed at Inlet Opening With Tubes in Place (FPS)	V_B Air Speed at Inlet Opening Without Tubes (FPS)	V_B/V_b Tube Correction Factor	Q Model Ventilation Rate (CFM)
0	210	1.26			1.20	1.51
	410	2.49				2.99
	600	3.72				4.46
	825	5.77	3.83	4.61		6.92
45	210	1.10			1.00	1.10
	410	2.36				2.36
	600	3.57				3.57
	825	5.23	3.52	3.52		5.23
90	210	0.60			1.00	0.60
	410	1.55				1.55
	600	2.30				2.30
	825	3.64	5.52	5.51		3.64
135	210	0.87			1.33	1.16
	410	1.92				2.55
	600	2.89				3.84
	825	4.39	3.42	4.54		5.84
180	210	0.93			1.15	1.07
	410	1.90				2.19
	600	3.02				3.47
	825	4.25	4.80	5.50		4.89
225	210	0.87			1.34	1.17
	410	2.06				2.76
	600	3.05				4.09
	825	4.28	3.29	4.41		5.74
315	210	1.07			1.10	1.18
	410	2.22				2.44
	600	3.48				3.83
	825	4.83	3.30	3.64		5.31

F is a Flow Correction Factor that gives the increment or decrement in flow due to unequal areas of the windward and leeward openings. Values of F may be obtained from Figures 3.1a and 3.1b. This data may not be extrapolated.

Table 3.6 shows values of the windward and the leeward wall opening areas, values of the factor F and the ventilation rates for all five models calculated using Equation (1). Figure 3.2 shows a comparison of model ventilation rates calculated using Equation (1) with the experimental values given in Tables 3.1 - 3.5. The data points in Figure 3.2 correspond to experimental values of the model ventilation rate for all values of the relative wind angle.

Figures 3.3 - 3.6 show the variations in ventilation rate per unit area of wall openings with the windward opening area expressed as a fraction of the total opening area. The data points correspond to experimental values of ventilation rate of all five models at all values of the relative wind angle.

Figures 3.7 - 3.11 show variations in the projected ventilation rates (using Equation 1) for each of the five shelter configurations with the approach wind speed. The shaded area in each figure shows the range of variations in ventilation rates due to changes in relative wind angle.

3.2 Technical Disucssion

Equation (1) is a simple, linear relation that enables one to estimate shelter ventilation rate as a function of the approach wind speed, area of windward openings and the ratio of areas of leeward and windward openings. (For a shelter of given total wall opening area, the ratio of leeward to windward opening area depends on the relative wind angle.) This equation was

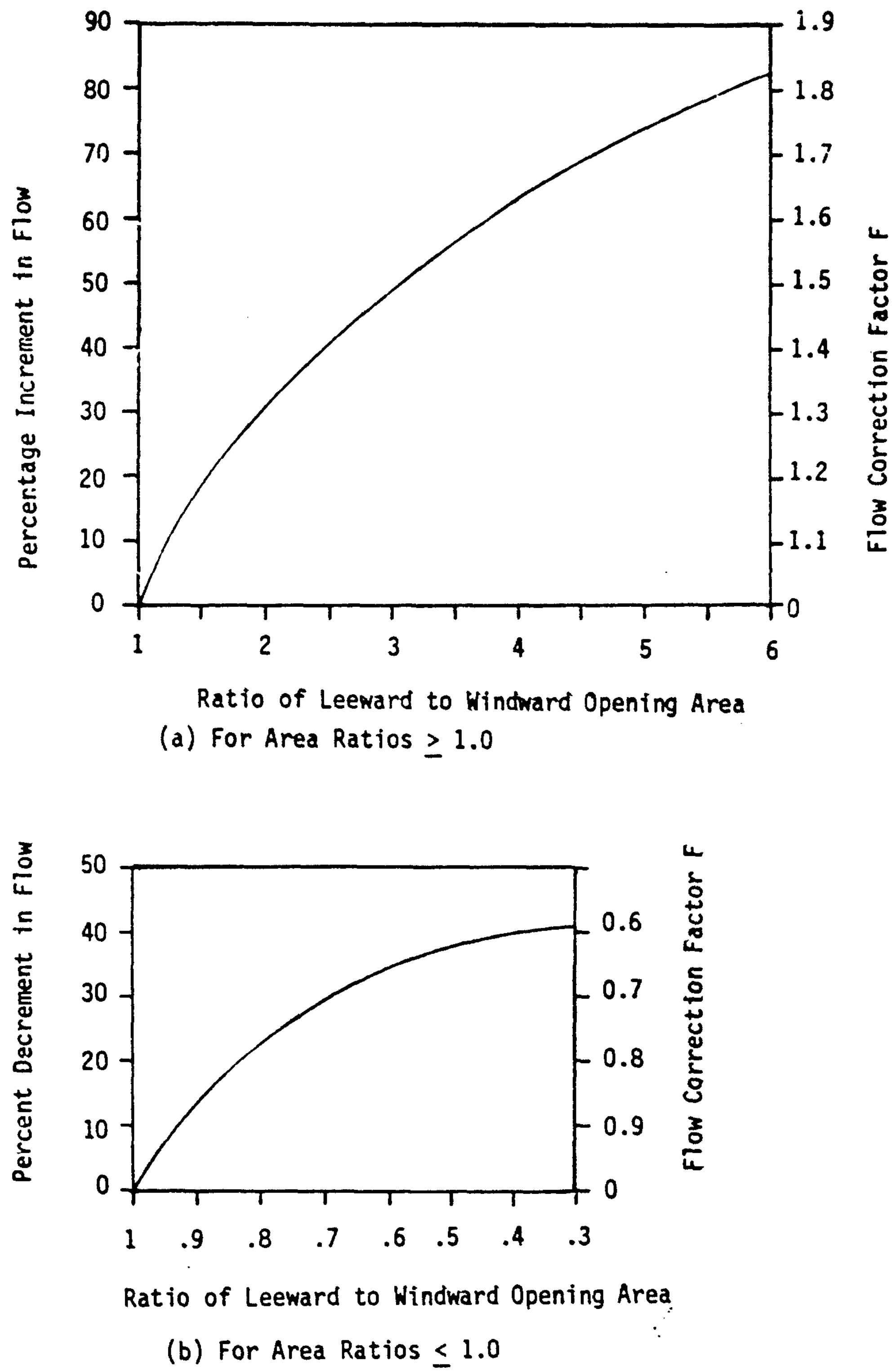

Figure 3.1 FLOW CHANGE DUE TO UNEQUAL AREAS OF WINDWARD AND LEEWARD OPENINGS

TABLE 3.6
PREDICTED MODEL VENTILATION RATES BASED ON EQUATION 1

Model Configuration	θ Relative Wind Angle (DEG.)	A_W Inlet Area Windward Sides (SQ.FT.)	A_L Outlet Area Leeward Sides (SQ.FT.)	A_L/A_W Area Ratio	F Flow Correction Factor	$Q = 0.31 \times A_W \times V_M \times F$ Predicted Model Ventilation Rate (CFM)			
						Approach Wind Speed (FPM)			
						210	410	600	825
A	0°	0.0162	0.0208	1.29	1.13	1.19	2.32	3.40	4.78
B		0.0162	0.0301	1.86	1.30	1.37	2.67	3.91	5.38
C		0.0231	0.0208	0.90	0.85	1.28	2.50	3.65	5.03
D		0.0162	0.0278	1.72	1.27	1.31	2.55	3.73	5.13
E		0.0231	0.0278	1.20	1.11	1.67	3.26	4.77	6.56
A	45°	0.0231	0.0139	0.60	0.65	0.98	1.91	2.80	3.94
B		0.0231	0.0231	1.00	1.00	1.50	2.94	4.30	5.92
C		0.0301	0.0139	0.46	0.61	1.19	2.33	3.41	4.69
D		0.0231	0.0208	0.90	0.85	1.28	2.50	3.65	5.03
E		0.0301	0.0208	0.69	0.70	1.37	2.68	3.92	5.38
A	90°	0.0069	0.0301	4.33	1.66	0.75	1.47	2.14	2.95
B		0.0069	0.0393	5.66	1.80	0.82	1.59	2.32	3.19
C		0.0069	0.0370	5.33	1.77	0.80	1.56	2.28	3.15
D		0.0069	0.0370	5.33	1.77	0.80	1.56	2.28	3.15
E		0.0069	0.0440	6.33	1.84	0.84	1.63	2.38	3.27
A	135°	0.0139	0.0231	1.67	1.26	1.14	2.22	3.25	4.47
B		0.0231	0.0231	1.00	1.00	1.50	2.94	4.30	5.92
C		0.0139	0.0301	2.17	1.36	1.23	2.40	3.51	4.83
D		0.0208	0.0231	1.11	1.07	1.45	2.83	4.14	5.70
E		0.0208	0.0301	1.44	1.20	1.63	3.18	4.65	6.39

TABLE 3.6 (Cont'd.)
PREDICTED MODEL VENTILATION RATES BASED ON EQUATION 1

Model Configuration	θ Relative Wind Angle (DEG.)	A_W Inlet Area Windward Sides (SQ.FT.)	A_L Outlet Area Leeward Sides (SQ.FT.)	A_L/A_W Area Ratio	F Flow Correction Factor	$Q = 0.31 \times A_W \times V_M \times F$ Predicted Model Ventilation Rate (CFM) Approach Wind Speed (FPM) 210	410	600	825
A	180°	0.0069	0.0301	4.33	1.66	0.75	1.47	2.14	2.95
B		0.0162	0.0301	1.86	1.30	1.37	2.67	3.91	5.38
C		0.0069	0.0370	5.33	1.77	0.80	1.56	2.28	3.15
D		0.0139	0.0301	2.17	1.36	1.23	2.40	3.51	4.83
E		0.0139	0.0370	2.67	1.45	1.32	2.56	3.75	5.15
A	225°	0.0139	0.0231	1.67	1.26	1.14	2.23	3.26	4.47
B		0.0231	0.0231	1.00	1.00	1.50	2.94	4.30	5.92
C		0.0139	0.0301	2.17	1.36	1.23	2.40	3.51	4.83
D		0.0208	0.0231	1.11	1.06	1.54	2.81	4.11	5.65
E		0.0208	0.0301	1.44	1.17	1.59	3.10	4.54	6.23
A	270°	0.0069	0.0301	4.33	1.66	0.75	1.47	2.14	2.95
B		0.0069	0.0393	5.66	1.80	0.82	1.59	2.32	3.19
C		0.0069	0.0370	5.33	1.77	0.80	1.56	2.28	3.15
D		0.0069	0.0370	5.33	1.77	0.80	1.56	2.28	3.15
E		0.0069	0.0440	6.33	1.84	0.84	1.63	2.38	3.27
A	315°	0.0231	0.0139	0.60	0.65	0.98	1.91	2.80	3.84
B		0.0231	0.0231	1.00	1.00	1.50	2.94	4.30	5.92
C		0.0301	0.0139	0.46	0.61	1.19	2.33	3.41	4.69
D		0.0231	0.0208	0.90	0.85	1.28	2.50	3.65	5.03
E		0.0301	0.0208	0.69	0.70	1.37	2.68	3.92	5.38

LEGEND

Q_1 is the ventilation rate calculated from Equation (1), values from Table 3.6.

Q_2 is the experimental value of ventilation rate, values from Tables 3.1 - 3.5.

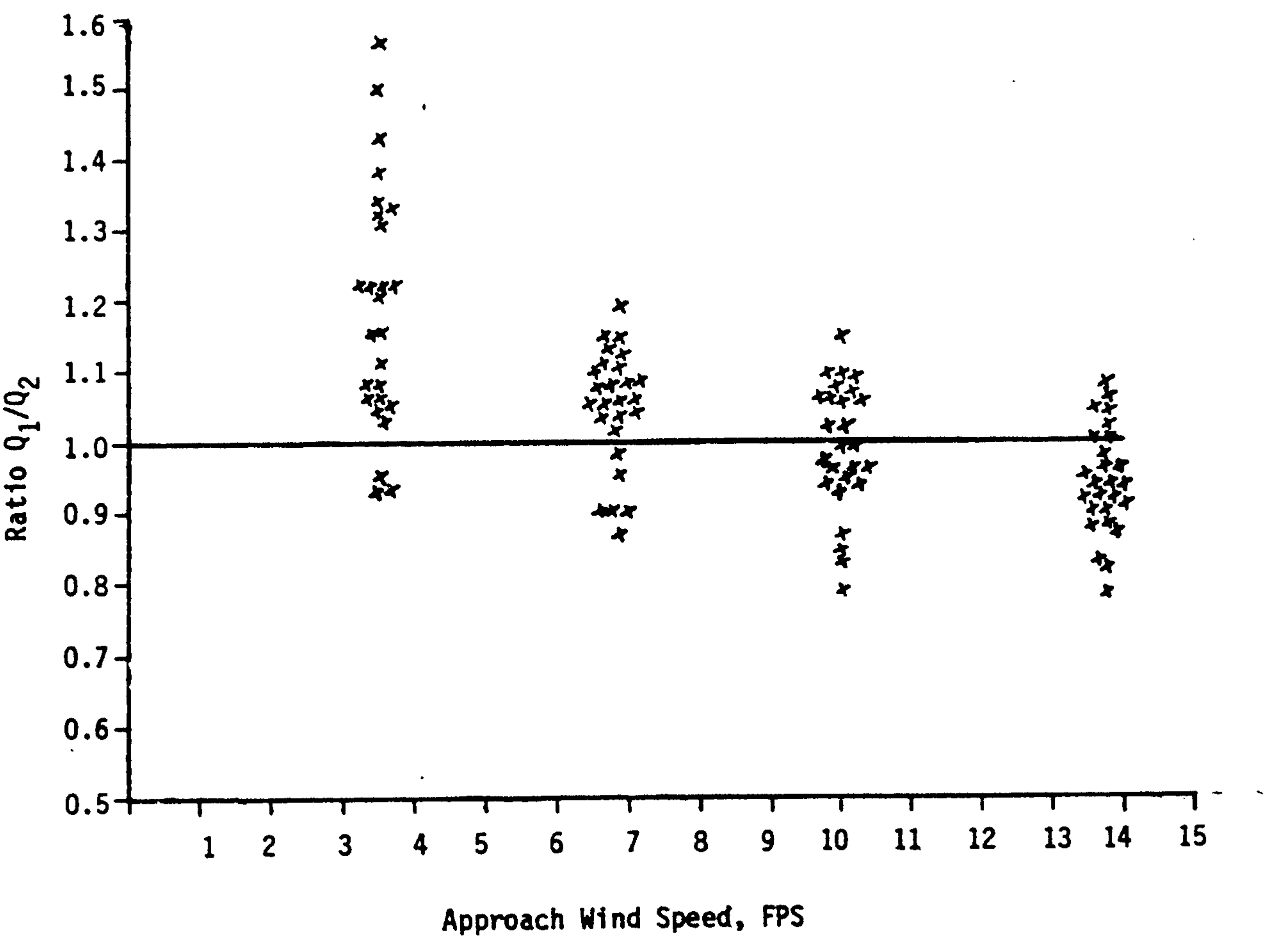

Figure 3.2 CALCULATED VERSUS MEASURED VENTILATION RATES

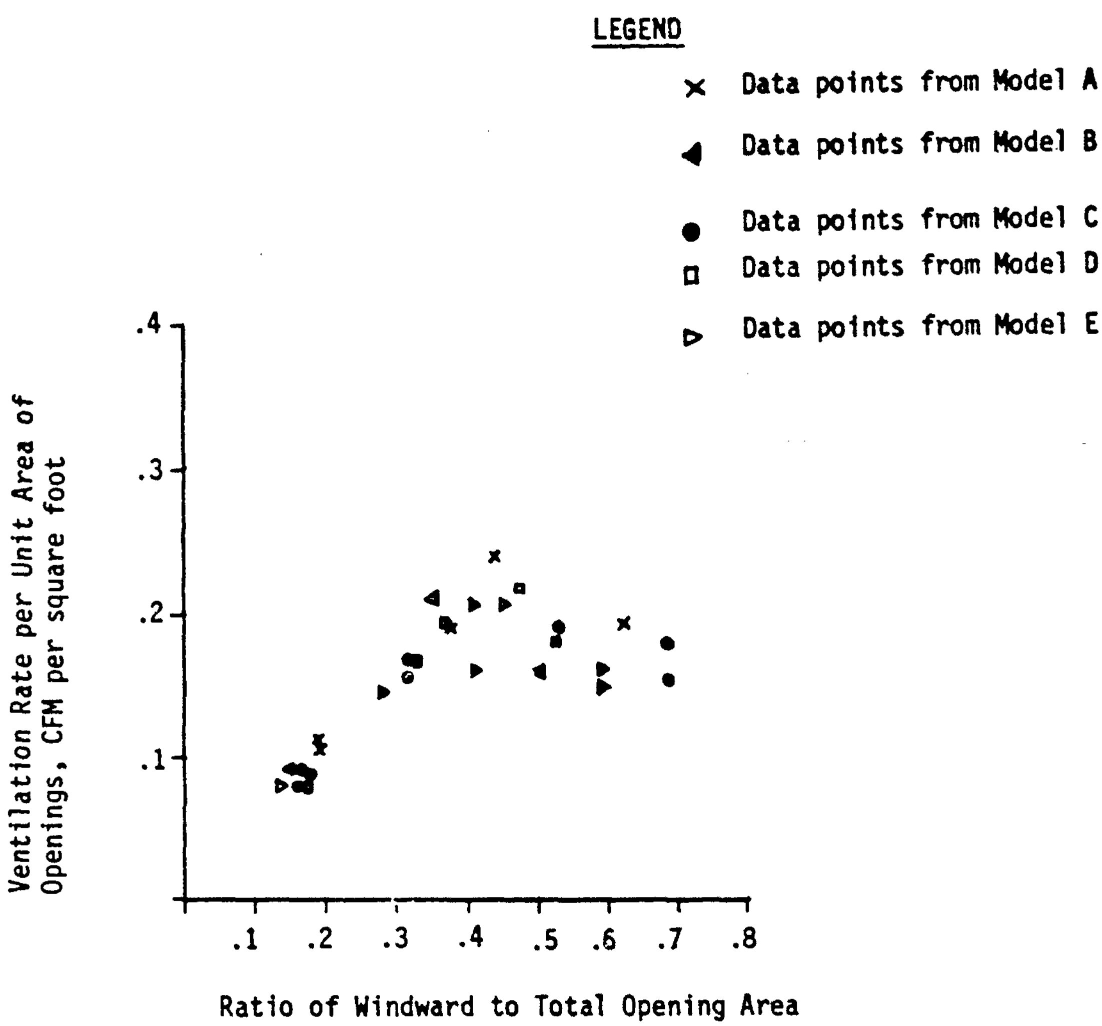

Figure 3.3 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 210 FPM

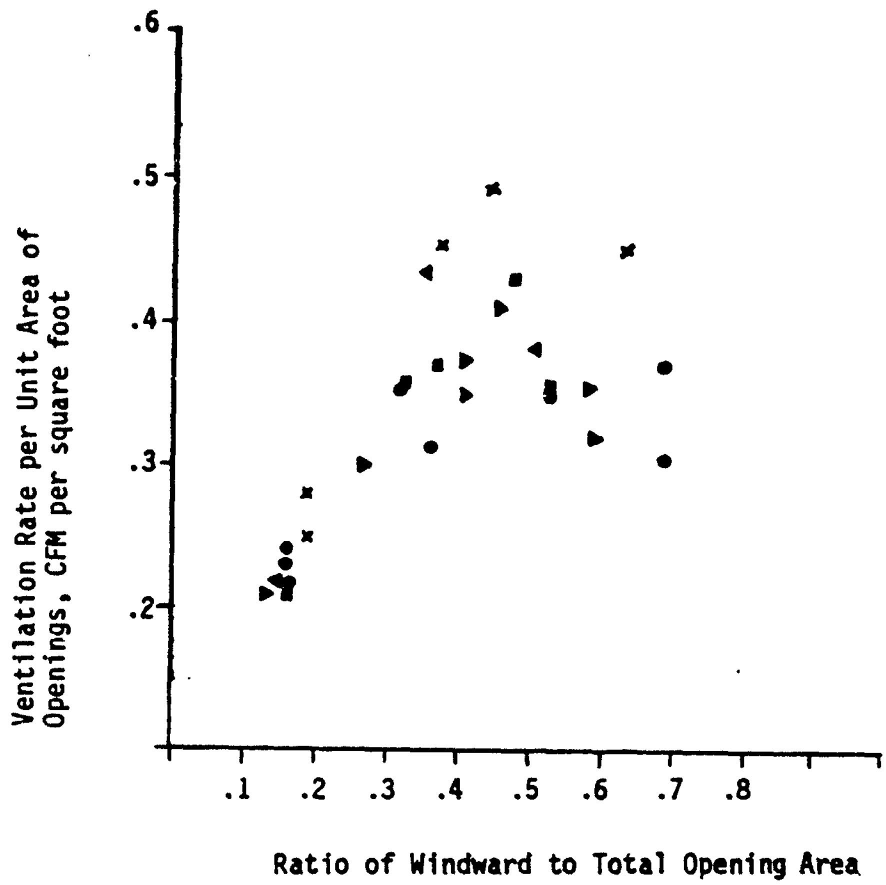

Figure 3.4 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 410 FPM

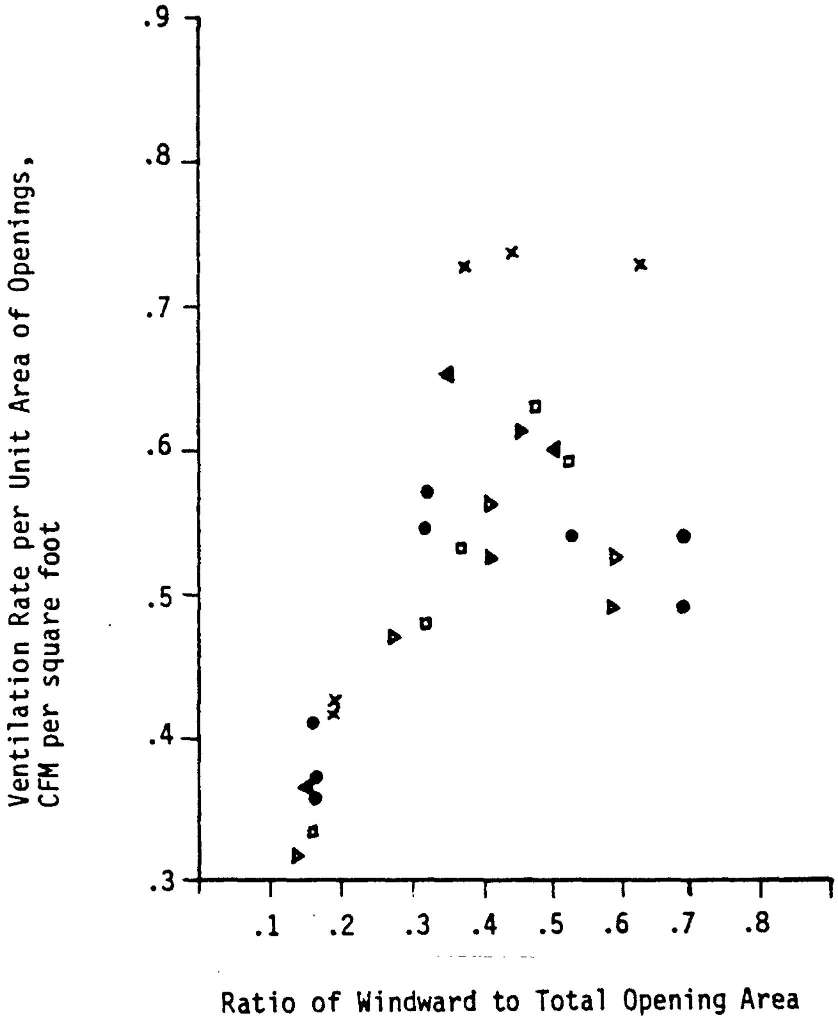

Figure 3.5 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 600 FPM

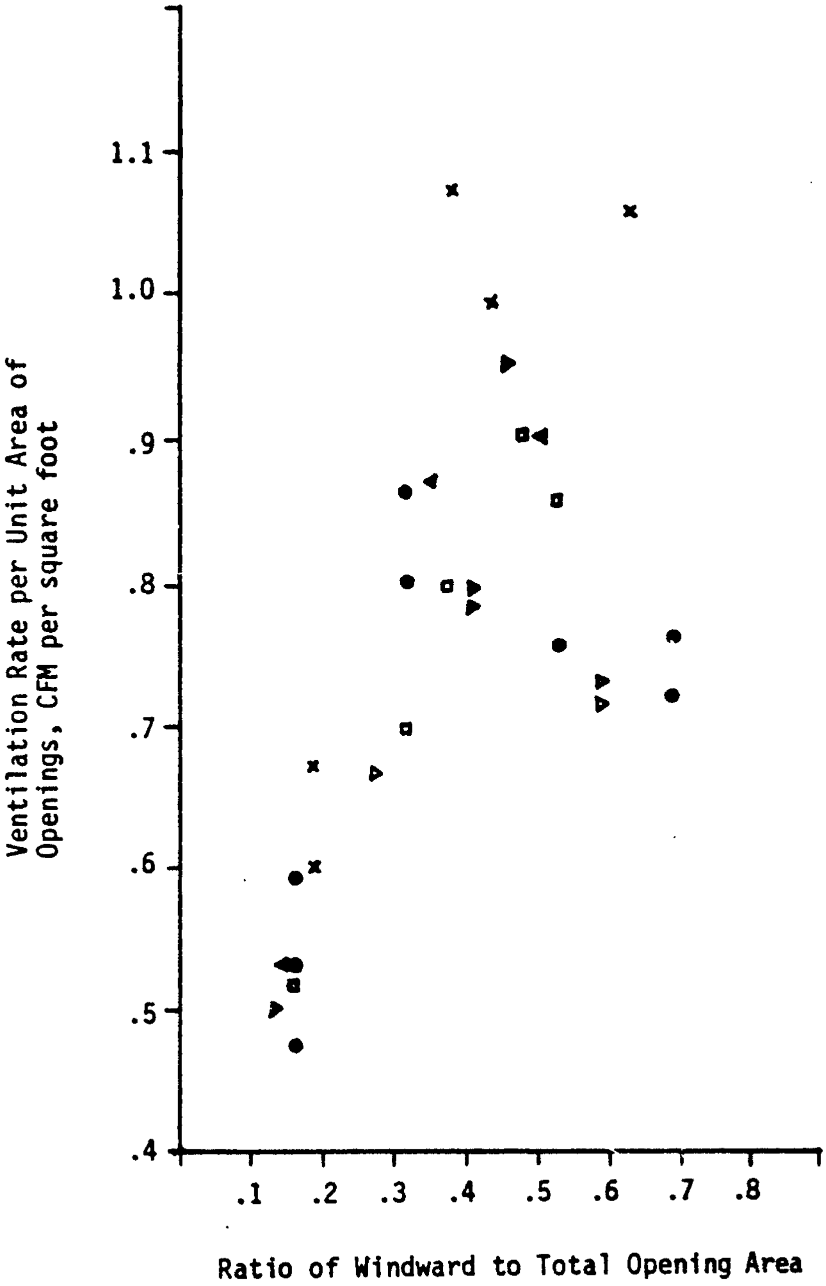

Figure 3.6 INFLUENCE OF OPENING DISTRIBUTION ON VENTILATION RATE PER UNIT OPENING AREA, WIND SPEED 825 FPM

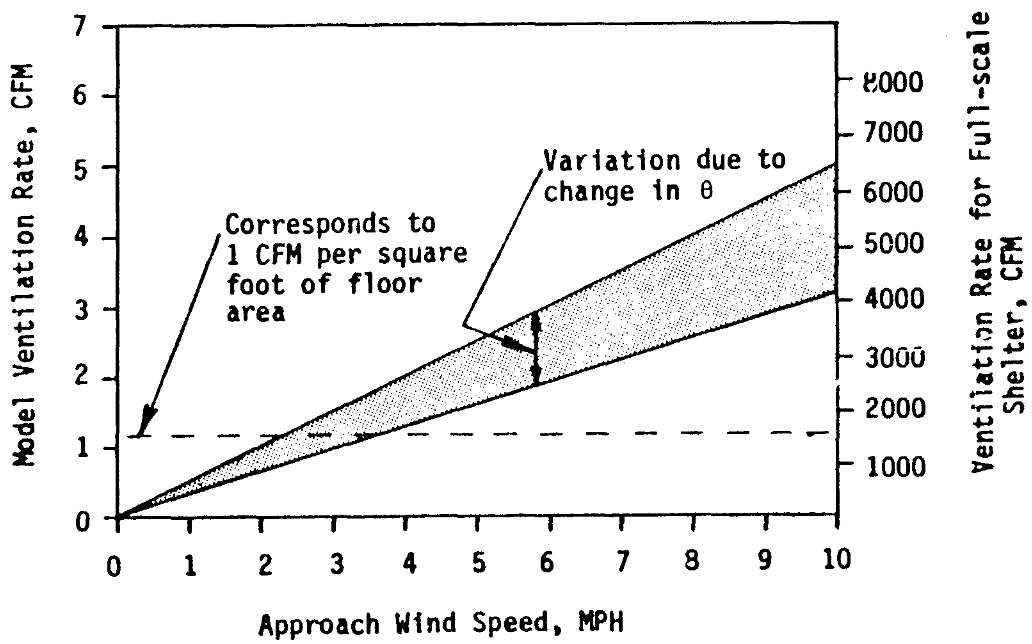

Figure 3.7 VENTILATION RATE VERSUS APPROACH WIND SPEED, SHELTER A

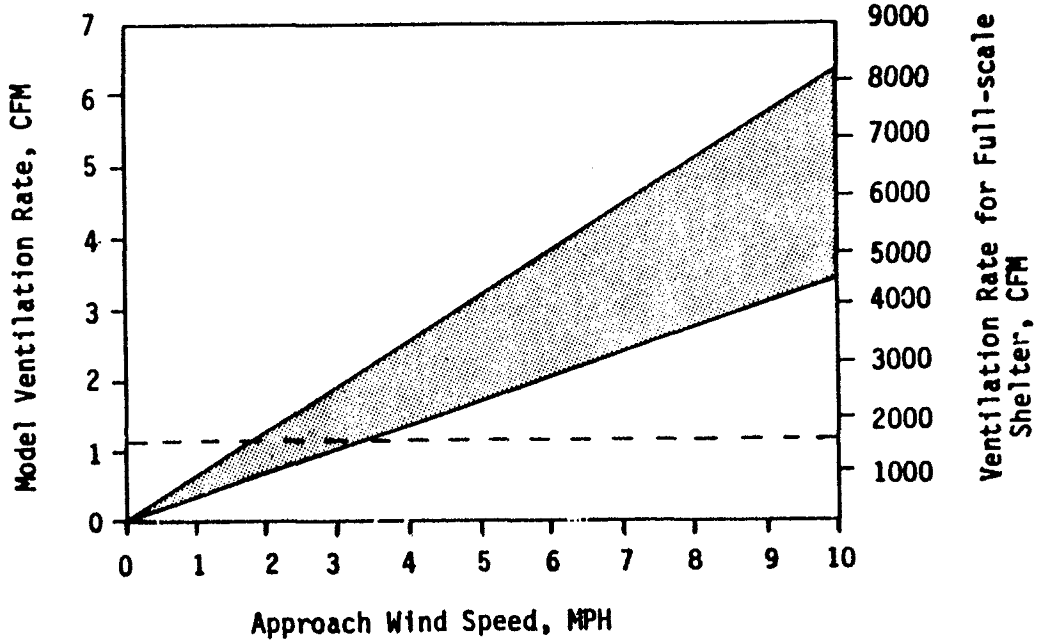

Figure 3.8 VENTILATION RATE VERSUS APPROACH WIND SPEED, SHELTER B

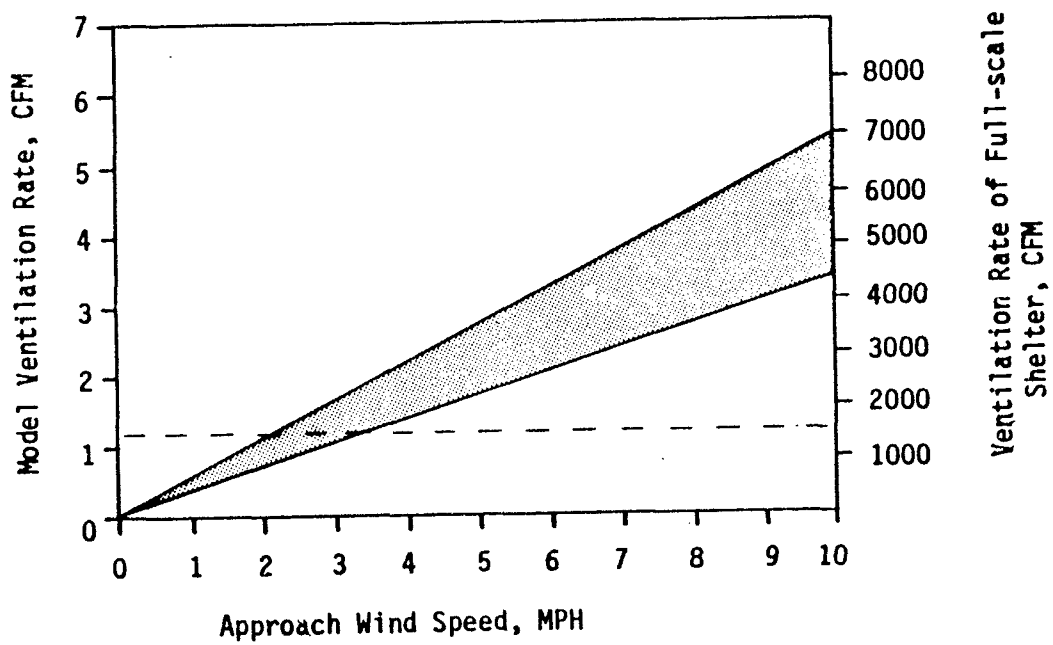

Figure 3.9 VENTILATION RATE VERSUS APPROACH WIND SPEED, SHELTER C

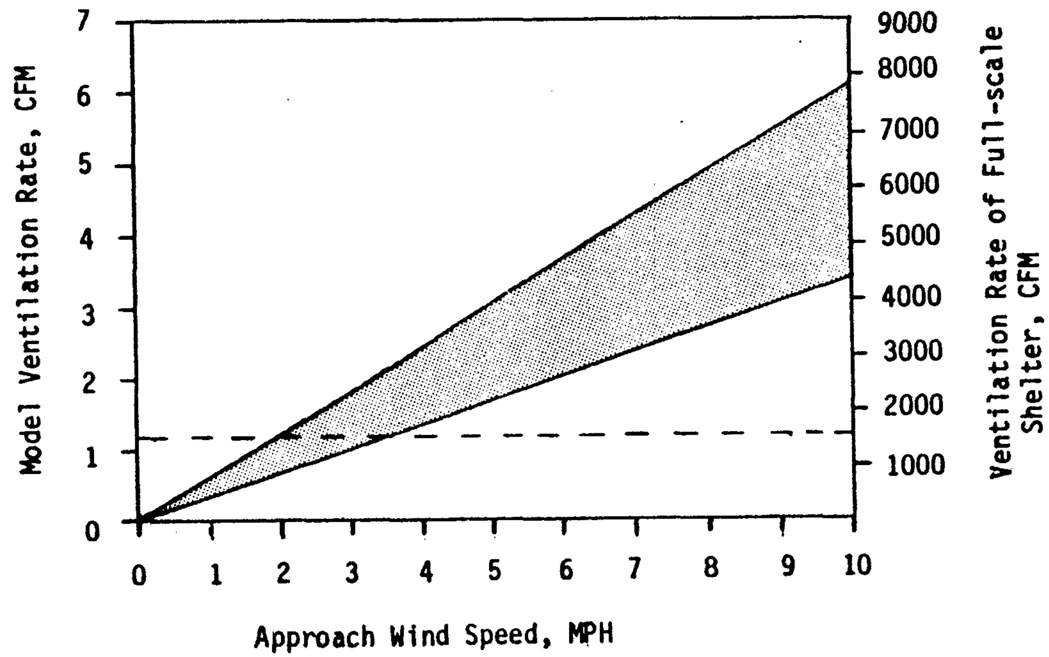

Figure 3.10 VENTILATION RATE VERSUS APPROACH WIND SPEED, SHELTER D

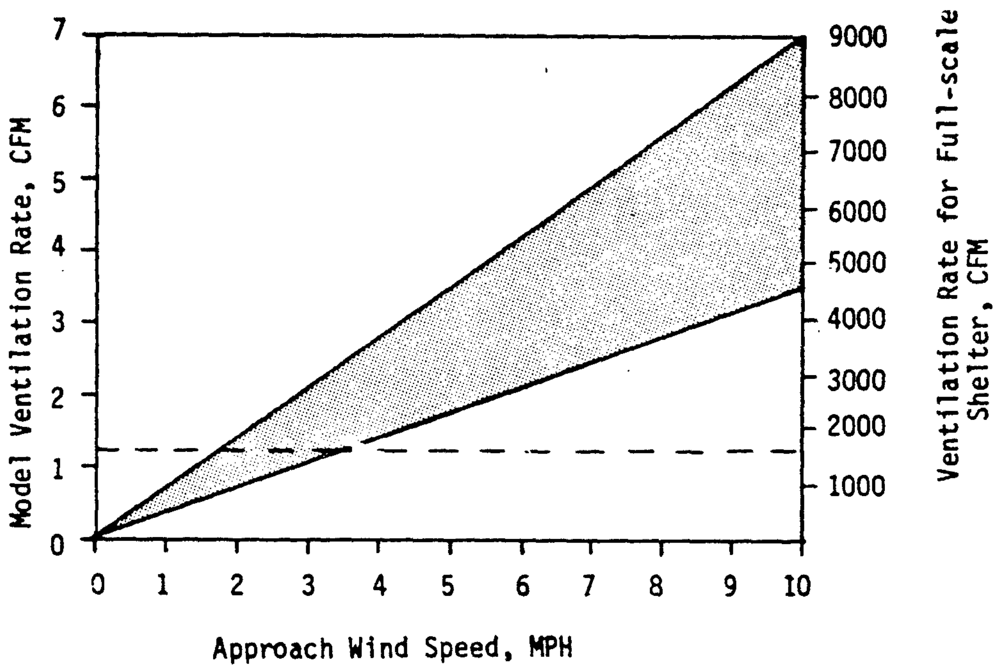

Figure 3.11 VENTILATION RATE VERSUS APPROACH WIND SPEED, SHELTER E

obtained by correlating experimental data from all five shelter models. As seen from Figure 3.2, the correlation is extremely good at the higher values of the approach wind speed. However, the correlation is weak at the lowest value of the approach wind speed tested. This is probably due to the inaccuracies in the measurement of axial velocities in the calibration tubes at such low values (less than 50 feet per minute).

Equation (1) is similar in form to Equation (12), Chapter 21 of Reference 3. The latter equation which is reproduced below, gives ventilation rates of buildings in general (residential, office, etc.).

$$Q = E \times A \times V \qquad \text{(Eqn. 2)}$$

where Q = Ventilation rate, CFM

A = Free area of inlet openings, square feet

V = Wind velocity, feet per minute

E = Effectiveness factor; 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds.

For buildings with equal areas of windward and leeward openings (for which the factor F in Equation (1) equals unity), the constant of proportionality in Equation (1) (equal to 0.31), agrees with that of Equation (2) for the case of diagonal winds. However, for perpendicular winds, values given by Equation (2) are substantially larger (up to 100%). It may be noted that Equation (1) was developed for shelters with earth berms. The berms probably aid ventilation when the approach wind is at an angle by acting as flow deflectors. This, together with the fact that the distribution of windward and leeward opening areas is often more favorable at diagonal winds than at perpendicular winds, is probably the reason why shelter ventilation rates at diagonal winds are often equal to or greater than those for perpendicular winds.

Use of Equation (2) for estimating building ventilation rates raises some ambiguities. References 3 and 8 define the independent variable A as the area of the inlet wall openings, whereas an earlier edition of ASHRAE Fundamentals (Ref. 9) defines it as the smaller of the inlet and outlet opening areas. Further, when openings are present in walls parallel to the direction of the approach wind, one is left guessing as to the proper value of this variable. In Equation (1), the variable A_w always denotes the total area of the windward openings. The increment or decrement of flow due to unequal areas of windward and leeward openings is accounted for by the factor F. For a building with unequal areas of openings on opposite walls, Equation (2) gives the same value of ventilation rate when the relative wind angle is changed by 180°. This was not found to be true for the shelter models studied. Equation (1), in which values of the factor F are taken from two different curves (Figures 3.1a and 3.1b) depending on whether the ratio (A_1/A_w) is greater than or less than unity, is found to give better correlation with experimental values. However, extrapolation of these curves beyond the ranges of the ratio (A_1/A_w) indicated in these figures is not recommended.

Figures 3.3 - 3.6 show that maximum values of ventilation rate per unit area of wall openings are obtained when the windward opening area is about 50% of the total. For all five models, the highest values of ventilation rate per unit area of wall openings were obtained when the windward opening area was between 30% and 60% of the total opening area. This observation was true for all values of the approach wind speed tested. It may be inferred that if openings are distributed over the walls such that the windward opening area is between 30% and 60% of the total opening area at any value of the relative wind angle, the ventilation rate per unit area of openings will not be very sensitive to the actual location and area of the individual openings. However, the air distribution inside the shelter, which is not discussed in this report, is likely to depend upon the location and area of the individual openings.

The ratio of total wall opening area to floor area of the shelter models in this study, varied from 3.1% to 4.3%. Ventilation rates for each of these models (calculated from Equation (1)) and the projected values for the full-scale shelters are shown in Figures 3.7 - 3.11. Ventilation rates for the entire range of relative wind angles (0° to 360°) fall within the shaded area. At any given speed of the approach wind, the range of variation in ventilation rate due to changes in wind direction (relative wind angle) is given by the vertical intercept within the shaded area. The horizontal broken line in these Figures corresponds to a ventilation rate of 1 cubic foot per minute per square foot of floor area. This corresponds to 10 CFM per occupant at an occupant density of 1 person per 10 square feet. It is seen that this rate of ventilation can be achieved in all the shelter configurations studied at approach wind speeds as low as 3.5 mph.*

*The available ventilation rates may be somewhat less than those projected in Figures 3.7 - 3.11 due to the additional resistance provided by the occupants. Reference (2) gives an estimate of reductions in ventilation rates due to occupants.

Section 4

SUMMARY AND RECOMMENDATIONS

A linear relation that yields wind-induced ventilation rates in bermed, above-ground fallout shelters in terms of the approach wind speed, areas of exterior wall openings and the ratio of windward to total opening area (which depends on the direction of the approach wind) has been formulated from the results of the model tests. This relation has the same form as that given in the ASHRAE Handbook of Fundamentals (Ref. 3, 9, 10) for estimating wind ventilation in general type buildings. However, there are considerable differences in the values predicted by these two equations, especially for perpendicular winds.

Models with five different opening configurations were used in the present tests. Total opening areas of these models varied from 2.5% to 3.44% of wall surface area (3.13% to 4.3% of floor area). Projected results show that, for all five configurations, ventilation rates of 1 CFM per square foot of floor area can be achieved at approach wind speeds as low as 3.5 mph.

Test results also showed that the highest values of shelter ventilation rate per unit area of wall openings are achieved when the ratio of windward to total opening area lies between 0.3 and 0.6. If this ratio of opening areas can be met at all wind directions (by proper distribution of openings over the walls), it follows that the shelter will have the highest ventilation rates per unit area of wall openings for all wind directions.

The present study has established a means of estimating wind ventilation in a bermed, one-room, above-ground shelter. The Option 1 study (Ref. 2) provided estimates of wind ventilation that can be achieved in a one-room, below-ground shelter by the use of passive flow enhancement devices (FEDs). That study also provided estimates of ventilation reductions due to the presence of shelter occupants and also due to an upstream building. The next step in the Shelter Ventilation Analysis Program should be to evaluate the changes in ventilation rates that occur due to the presence of internal partitions (multi-room shelters) in both above-ground and below-ground shelters. The influence of internal partitions on shelter ventilation rate will probably be difficult to quantify. However, with proper areas and distributions of interior wall openings, reductions in ventilation rates might become insignficant. Another important area where there is a lack of available data relates to the reductions in ventilation rate for an above-ground shelter due to adjacent buildings (flow obstacles) which shield the shelter on one or more of its sides. Therefore, it is proposed that future work be directed towards (1) establishing a means to estimate ventilation reductions in above-ground and below-ground shelters due to internal partitions and setting guidelines to minimize such reductions and (2) providing estimates of ventilation reductions in bermed above-ground shelters due to buildings or other sturctures shielding one or more of its sides and establishing the minimum distances between the shelter and the neighboring buildings necessary to minimize these ventilation reductions.

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FEMA Contract No. EMW-C-0633, FEMA Work Unit 1217I
by C. K. Krishnakumar, C. K. Schafer, S. F. Fields, R. H. Henninger
September 1984 (UNCLASSIFIED) pp 60

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used in these tests. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas and the velocity of the approach wind. Results were compared with those projected from available correlations for general type buildings.

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